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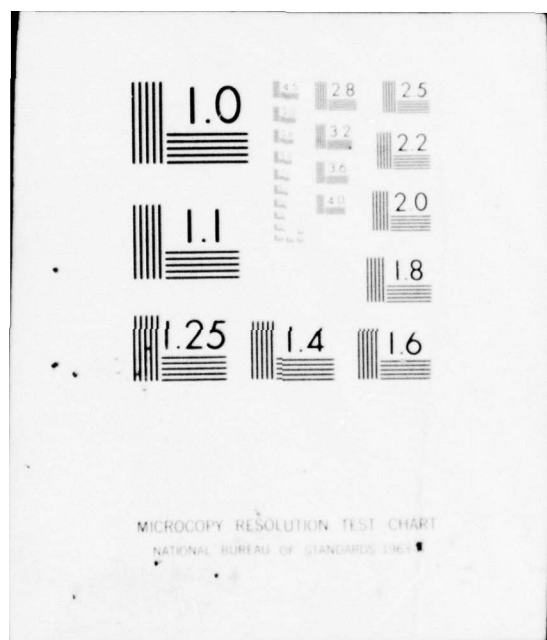
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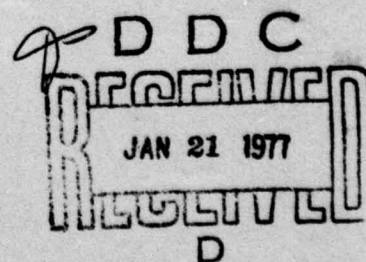
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SCANNING CURSOR TECHNIQUES

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21. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the effort to design, fabricate and test a digitizing cursor with integral line centering capability. The resultant cursor is transmissive in nature utilizing a linear photodiode array, an optical system and array signal processing electronics. Processor output is a binary count representing position of the image traced feature on the array. A computer algorithm uses the information as a corrective term to yield accurate coordinate data. Computer-generated rotational commands serve to continuously position the array to be orthogonal to the feature to ensure maximum accuracy in		

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tracing features containing curvatures or forming closed contours. Accuracy of $\pm .003$ inch is obtainable in digitizing with the cursor.

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PREFACE

The work reported in this Technical Report was performed under RADC Contract F30602-74-C-0318 entitled, Scanning Cursor Techniques, by the RCA Advanced Technology Laboratories (ATL), Camden, NJ.

The following RCA personnel contributed to this program: G. W. Hunka, L. Toombs, M. Soffa, E. Hutto, and C. Lauxen. J. J. Ruduick acted as Project Leader.

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EVALUATION

This report includes an area which supports an integrated program designed to introduce automation into the cartographic field; specifically, it addresses the need to evolve and implement approaches which will increase the overall conversion rate, but which will maintain accuracy.

It directly addresses the needs of TPO 3 which has the major goal of providing new techniques to improve the accuracy and efficiency of the cartographic processes.

In using a manual input digitizer as an approach to the data conversion problem, the process is tedious and error prone. By using an aided-track digitizing cursor and allowing the operator to make small errors which are automatically computer-corrected, the accuracy of the digitized data is improved and simultaneously operator efficiency and output are increased.

Stanley P. Damon

STANLEY P. DAMON
Project Engineer

Section I

INTRODUCTION

A. BACKGROUND

Currently, manual tracing operations on digitizing tables are used in converting cartographic feature coordinates to digital values for storage and subsequent processing. The designation of a feature includes any line function on the map serving to define both man-made artifacts and geographic boundaries such as roads, rivers, coastlines, contour lines, etc. whose point-by-point position can be given using a coordinate system. This procedure consists of maintaining a hand-held cursor cross-hair centered over the feature being digitized. Cursor position is sensed by various techniques ranging from servoed slaved carriages linked to optical encoders to a coded grid embedded in the table surface.

The inherent accuracies cannot be consistently met because the tracing process becomes quite tedious; operators cannot consistently perform operations to the inherent machine accuracies. Consequently, this operation is time consuming and produces errors that necessitate costly digital editing efforts.

This program has an objective to incorporate a device to sense small position variations of the map feature relative to its initial position as it is traced; these variations are then used to generate corrections to the encoded cursor coordinate values. By allowing the operator to make small errors which are automatically computer-corrected, the overall process is improved in its digitizing accuracy, and at the same time operator efficiency and output are increased.

Use of a Gradicon table was proposed to establish the feasibility of this concept. Since the Gradicon table is backlighted, it was ideally suited toward an approach which incorporated a linear photosensitive array to sense variations of the traced feature position. Extension of the concept for use on opaque digitizing tables by an illumination source contained within the cursor also seemed feasible, thus providing operational flexibility.

B. AIDED-TRACK CURSOR CONCEPT: PRINCIPLES OF OPERATION

1. Line Sensor Aided-Tracking

Use of a linear photosensitive array located in and aligned to the cursor permits a direct means for measuring the position deviation of a map feature imaged on the array.

The operator must follow the feature to be digitized with sufficient accuracy to keep the feature within a tracking circle on the reticle, shown in Figure 1. The circle diameter is in the order of a 1/16 inch, based on a 32-element array on 0.002-inch centers.

2. Generation of Correction Factors

Dimensional information of the intersection of the line array and the tracked feature can be derived from the array output. This value and the known angle of the array with respect to the coordinate axis allows the X and Y corrective terms to be determined. This process is shown in Figure 2, for the simplified case of a linearized trace feature. (Note that an orthogonal array position has been assumed. The array is in fact computer commanded to orthogonal positions, which is a unique concept of this aided-track cursor design.) The feature to be digitized is shown as a solid line.

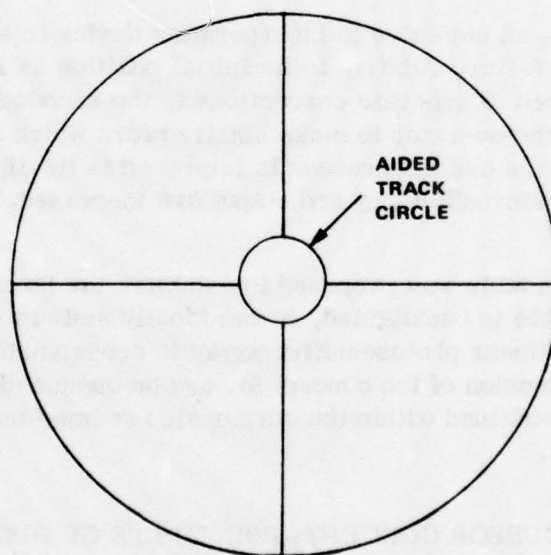
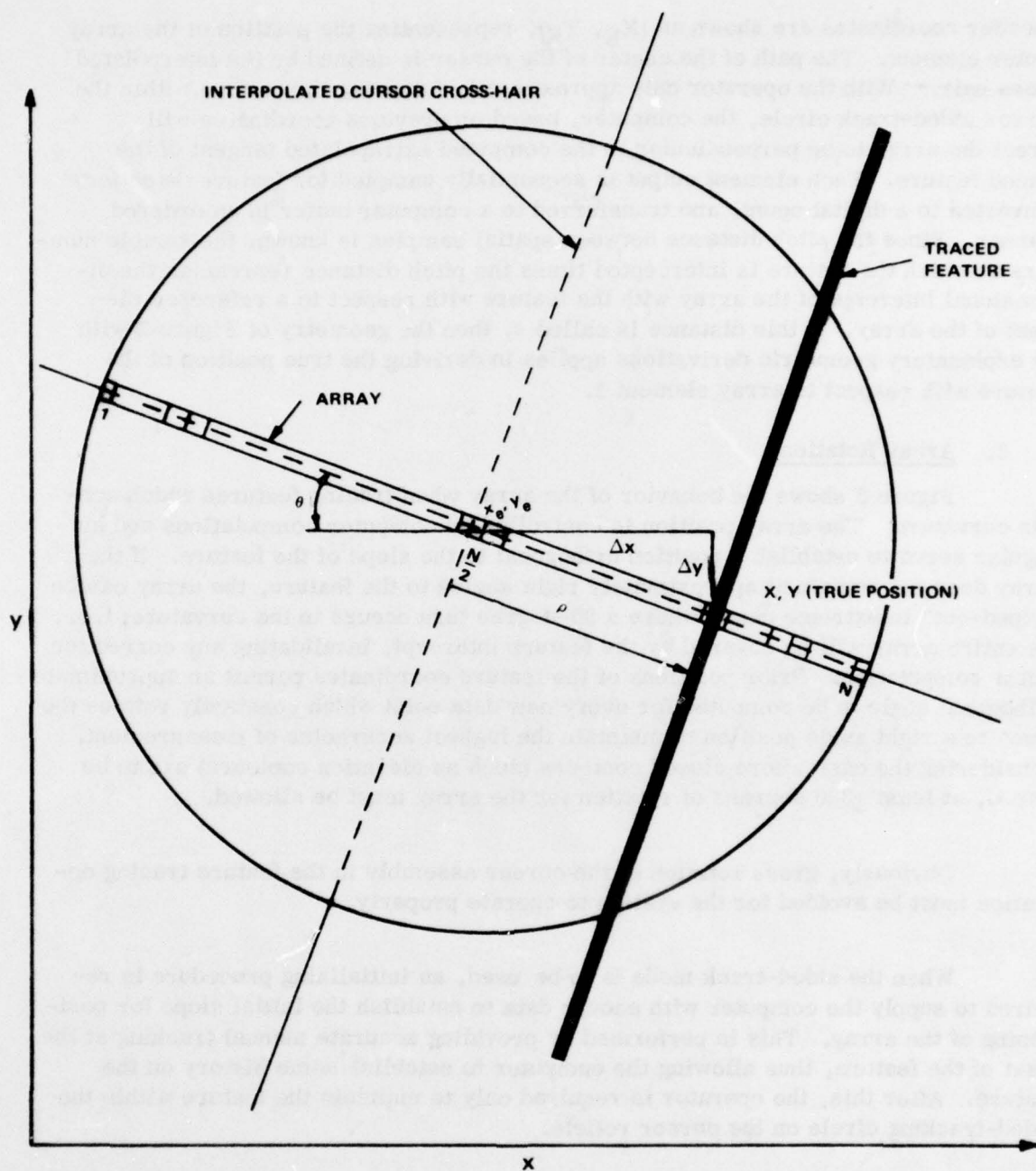


Figure 1. Cursor fiducial markings showing the aided-track circle. In operation feature being tracked must be maintained within aided-track circle to generate coordinate correction factors.



$$\text{TRUE } X = x_e + \Delta x \text{ where } \Delta x = \rho \cos \theta$$

$$\text{TRUE } Y = y_e - \Delta y \text{ where } \Delta y = \rho \sin \theta$$

Figure 2. Geometry for computing correction factors to modify encoder output.

Encoder coordinates are shown as (X_E, Y_E) , representing the position of the array center element. The path of the center of the cursor is defined by the interpolated cross hair.* With the operator only approximately following the feature within the cursor aided-track circle, the computer, based on previous coordinates will direct the array to be perpendicular to the computed extrapolated tangent of the traced feature. Each element output is sequentially sampled for feature detection, converted to a digital count, and transferred to a computer buffer in an ordered manner. Since the pitch distance between spatial samples is known, the sample numbers at which the feature is intercepted times the pitch distance represents the dimensional intercept of the array with the feature with respect to a reference element of the array. If this distance is called ρ , then the geometry of Figure 2 with its explanatory geometric derivations applies in deriving the true position of the feature with respect to array element 1.

3. Array Rotation

Figure 3 shows the behavior of the array when tracing features which contain curvature. The array position is controlled by computer computations and an angular servo to establish a position orthogonal to the slope of the feature. If the array does not remain at approximately right angles to the feature, the array can be "wiped-out" in extreme cases where a 90-degree turn occurs in the curvature; i.e., the entire array will be covered by the feature intercept, invalidating any correction factor computation. Prior positions of the feature coordinates permit an approximate orthogonal angle to be computed for every new data point which constantly rotates the array to a right angle position to maintain the highest accuracies of measurement. Considering the case where closed contours (such as elevation contours) are to be traced, at least ± 360 degrees of rotation for the array must be allowed.

Obviously, gross rotation of the cursor assembly in the feature tracing operation must be avoided for the system to operate properly.

When the aided-track mode is to be used, an initializing procedure is required to supply the computer with enough data to establish the initial slope for positioning of the array. This is performed by providing accurate manual tracking at the start of the feature, thus allowing the computer to establish some history on the feature. After this, the operator is required only to maintain the feature within the aided-tracking circle on the cursor reticle.

*Because a computer is used in determining the correction factors, any constant offset of the array with respect to the true encoder position can be corrected for in the computational algorithms; offset determinations are discussed in Section VI. D, with the corrective algorithm given in Section VI. E.

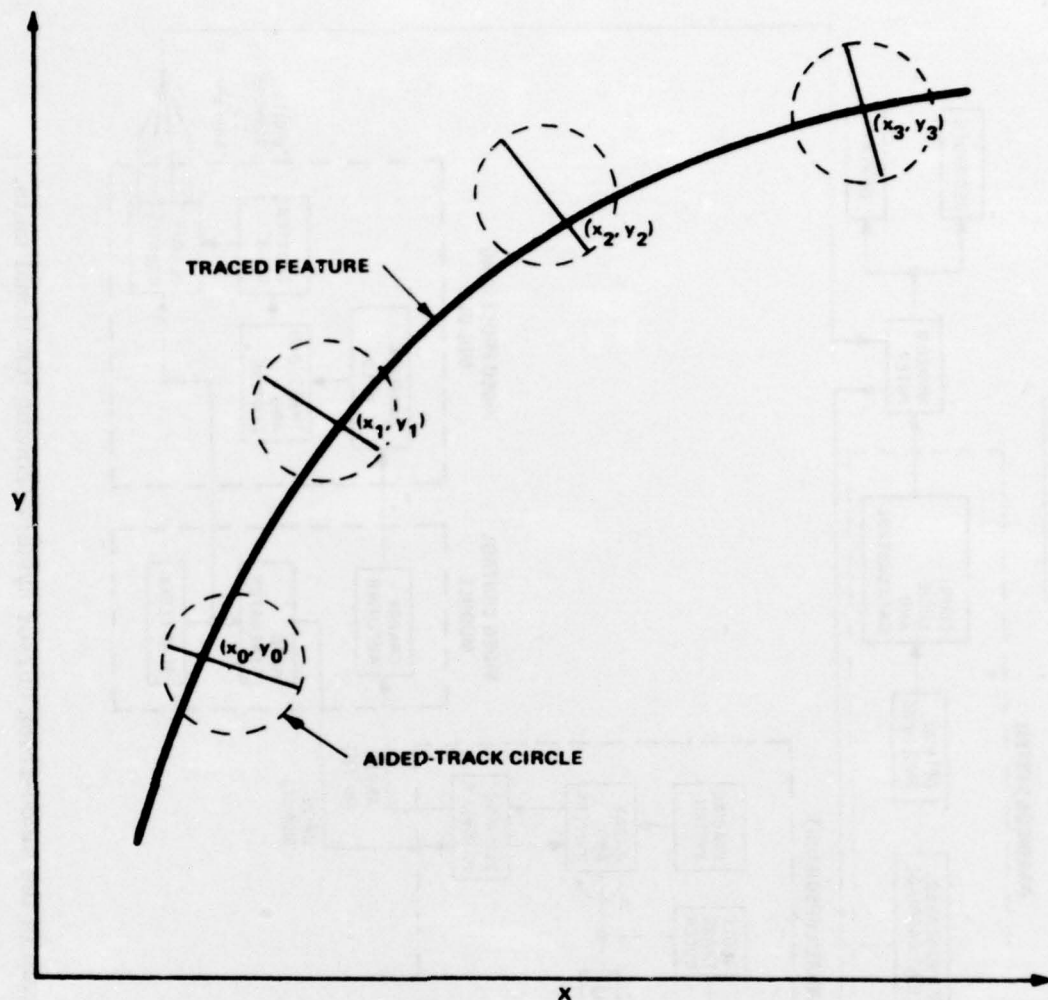


Figure 3. Rotation of the array to remain orthogonal to the traced feature allows an accurate estimation of line position which is unaffected by feature curvature.

4. System Integration

The concept of the aided-track cursor as incorporated into existing cartographic equipment is shown in Figure 4.

The Gradicon Digitizing System, the minicomputer, and the display terminal are part of the present cartographic facility; the additional modules shown provide the digitizing station with an aided-track operational mode. Following sections of this report describe the modules in detail.

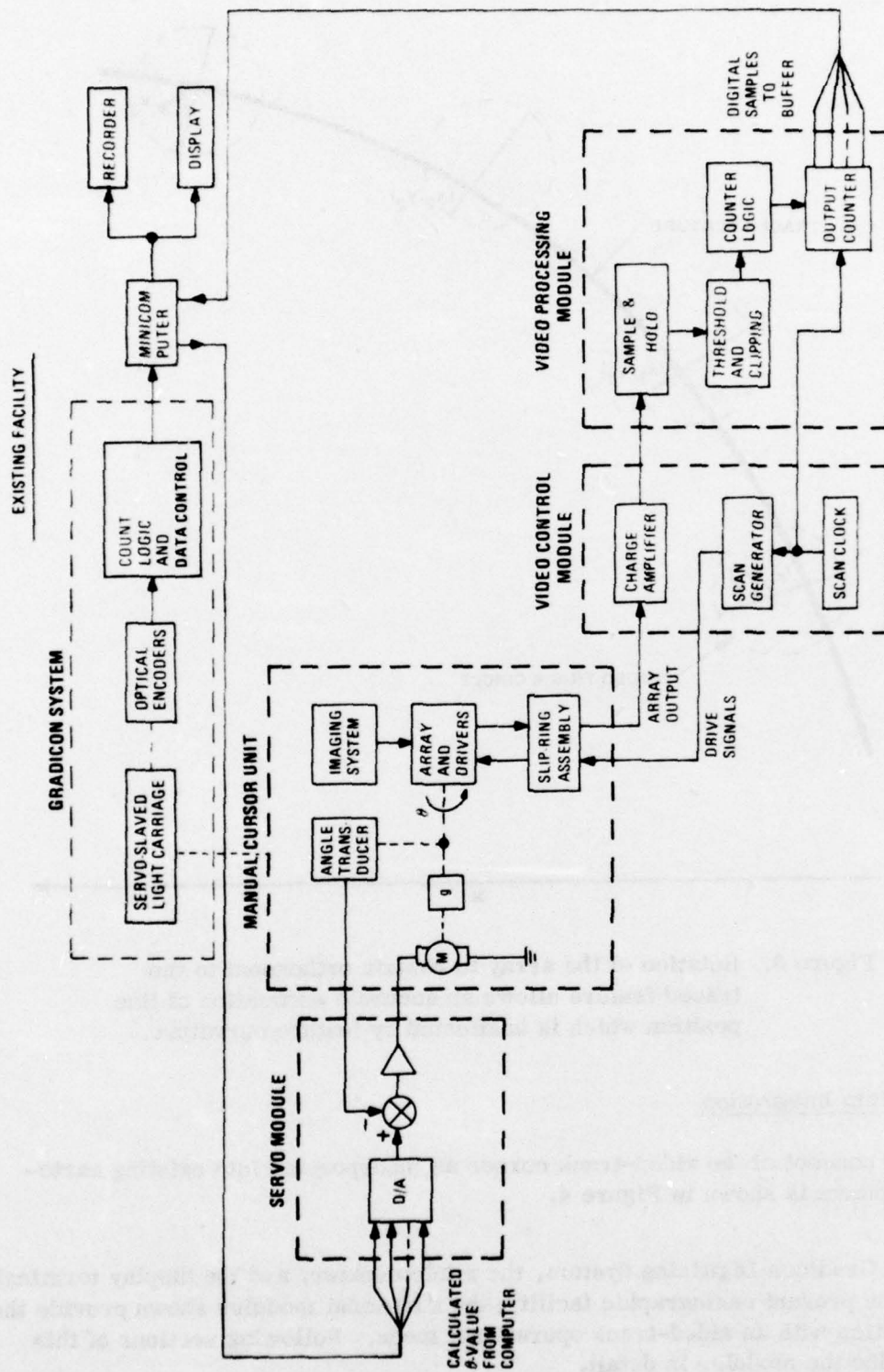


Figure 4. Block diagram of the aided-track cursor system showing functional units.

Section II

SYSTEM DESCRIPTION

A. GRADICON DIGITIZING SYSTEM

1. General Description

When drawings, photographs or other graphic data are being analyzed, it is often necessary to identify and record certain features in terms of their X and Y coordinates. The coordinate values, when recorded, can be utilized in computer programs for future modification or editing, and rapid regeneration of the manuscript by a writing device.

The GRADICON* (GRAphic to DIGital CONverter) is a manual system which enables the operator to digitize graphic data. The positional information is displayed numerically, in terms of the X and Y coordinates, or recorded in a data processing format.

The GRADICON system is comprised of three major units: The 48-inch x 60-inch glass top digitizing table, the electronic console and the optional output device, in this case an Imlac PDS-1D minicomputer.

2. Position Encoding

A hand-held cursor is used to mark the point to be digitized by means of a crosshair intercept. This cursor incorporates a coil which senses an electrically generated signal. A generating coil, located below the table and attached to a mechanical gantry, follows the cursor as it moves. Mounted on the gantry is a light source used to backlight the manuscript being digitized. This generating coil repositions itself immediately under the cursor. This is accomplished by an electromagnetic servo system and two servomotors which move the generating coil in the X and Y axes.

As soon as the hand-held cursor is moved to the required location, the displacement is detected by the generating coil. An error signal is then generated which causes the two servomotors to move the generating coil. The circuit is null seeking and, therefore, the generating coil follows up and homes on the cursor. It is moved until it is located below the cursor. The movement of each servomotor rotates an

*Gradicon is the trademark name for this table manufactured by Instronics Limited, Stittsville, Ontario.

encoder to provide a signal which is proportional to displacement along that particular axis.

The rotational signals are fed to a visual readout in an electronics console where a numerical value of the position is displayed. Therefore, as the cursor is moved, the numerical values change rapidly so that coordinate values are displayed visually, and simultaneously transferred to an Imlac - 1DS minicomputer, used as a video display terminal.

3. Modes of Operation

The normal operating modes which can be selected for the aided-track cursor mode are given below:

- a) Point Mode. Recordings made in the point mode of operation are related to the cursor position only. Each time that the operator depresses a cursor push-button or the foot switch, the X and Y coordinate position of the cursor is transmitted to the recording device or to the computer. This is a manual digitizing mode as opposed to the continuous output data stream obtained in the incremental mode.
- b) Incremental Mode. In the incremental mode, the operator may select an imaginary grid with vertical (X) or horizontal (y) or both. Spacing this grid will cause the digitizer to provide an output to the recording device or computer each time that the cursor traverses an imaginary vertical or horizontal grid line. A three-digit thumbwheel switch (Increment Select Switch) allows increment spacing intervals of from 0.002 inch to 0.998 inch in X or Y.*

Absolute readings recorded in either the point or incremental modes represent the displacement of the coordinates measured from the zero origin or reference origin. For simplicity, operation with the aided-track cursor is designed for first quadrant operation, i.e., positive values of x and y only; programming changes would permit operation in all quadrants. For purposes of demonstrating the feasibility of the aided-track concept, the added programming complexity was not deemed technically significant toward meeting the objectives of the program.

*On the basis of these preliminary specifications, the design of the aided-track cursor was based on incremental motions of 0.010 inch. As it developed, the RADC Gradicon was calibrated in micrometers, requiring dimensional conversion factors to be applied in the computer algorithms. Approximation errors are discussed in Section III. F.

B. AIDED-TRACK CURSOR SYSTEM

1. Description of the Aided-Track Cursor

The fully-assembled feasibility model of the aided-track cursor is shown in Figure 5. This unit is capable of remote operation from the processing modules within a 3-ft-diameter range. The housing (containing the electromechanical and optical components, and the photosensitive array) captures the existing cursor, whose push-button switch controls are on the left side. The operator viewing port is in the forward sloping portion of the unit. At the top of the housing, there is an error reset switch, as well as the control switch for activating the array rotational servo. In the off position, the array zero degree position is assumed. Two LEDs are provided on the forward portion of the switch housing to indicate servo on-off mode and a data error indicator.

The overall size of this working feasibility model is determined by the operator viewing area desired. In a later section (Section VI. B), a second-generation model is described which substantially reduces the overall size of the cursor assembly by decreasing the viewing diameter from 2 inches to 1 inch. Comparative photographs are included in Section VI. B illustrating the improvement in form factor achieved by this simple change.

The electromechanical system contained in the cursor housing is shown in Figure 6. The array and its driver circuitry are located on the rotatable mount shown. This mount is rotated by a ring gear so as to position the array orthogonal to the traced feature. A dc servoed motor is geared to the mount as shown, and follows the computer-derived angular commands. A 10-turn potentiometer, providing the feedback voltage, is driven by the ring gear; 2:1 gearing allows the potentiometer to travel a maximum of +900 degrees if necessary, and provides adequate margin for tracing closed contour lines.

Electrical signals required for the rotating assembly (phase voltages, array output, power, and scan control signal) are supplied through a miniature slip-ring assembly located on the reverse side of the mount; this side is shown in Figure 7.

In addition to the electromechanical system described, the cursor housing also contains an optical system to allow an operator to simultaneously view the feature as it is being imaged onto the array. Figure 8 is a diagram of the optical system used. Simultaneous viewing and imaging are achieved by use of the 30% transmissive neutral density beam splitter shown. Focusing of the 1:1 imaging lens, a coated achromatic lens with a 36-mm focal length, is possible by means of an external screw adjustment.



Figure 5. Aided-track cursor assembly (feasibility model).

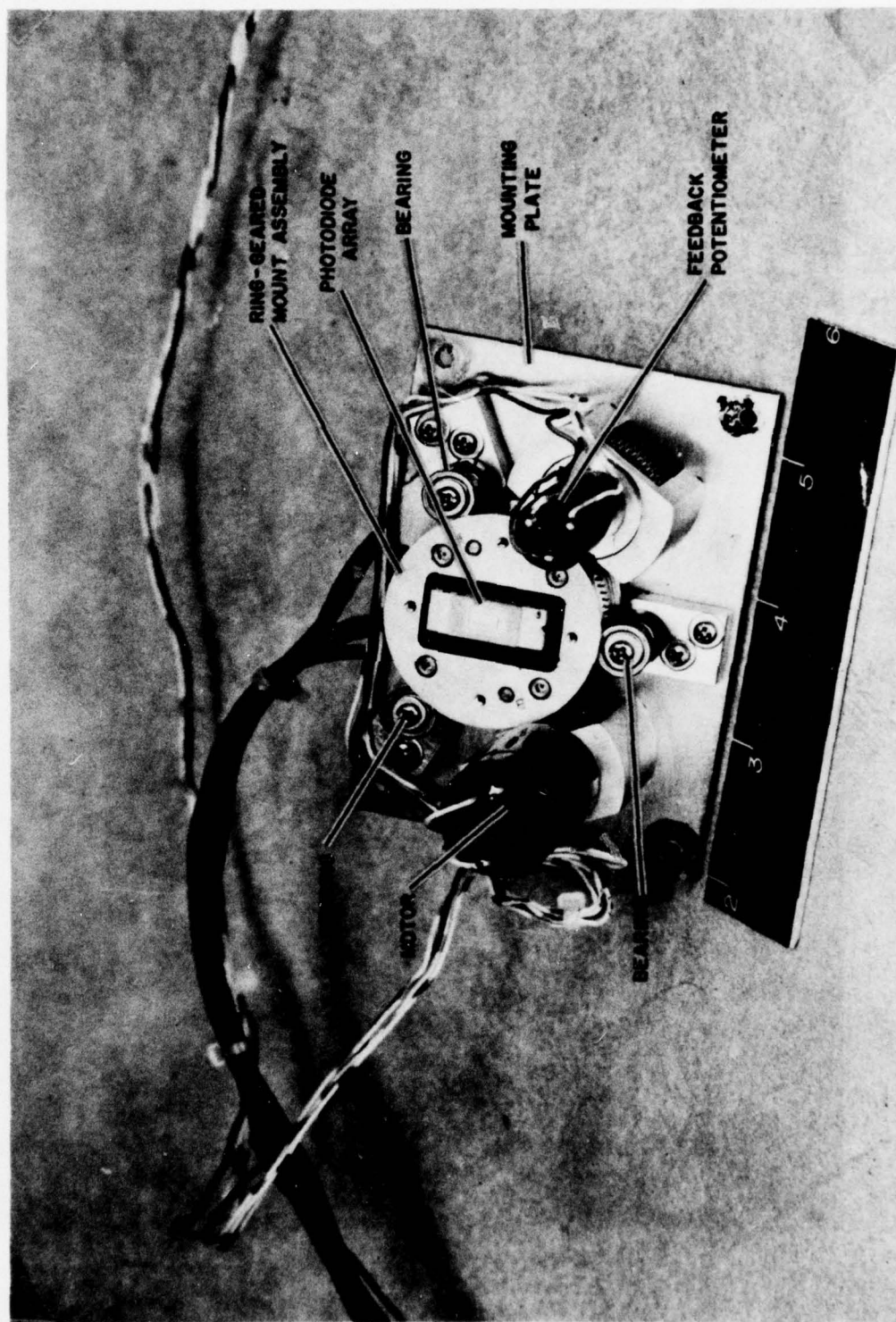


Figure 6. Cursor assembly, mechanical arrangement.

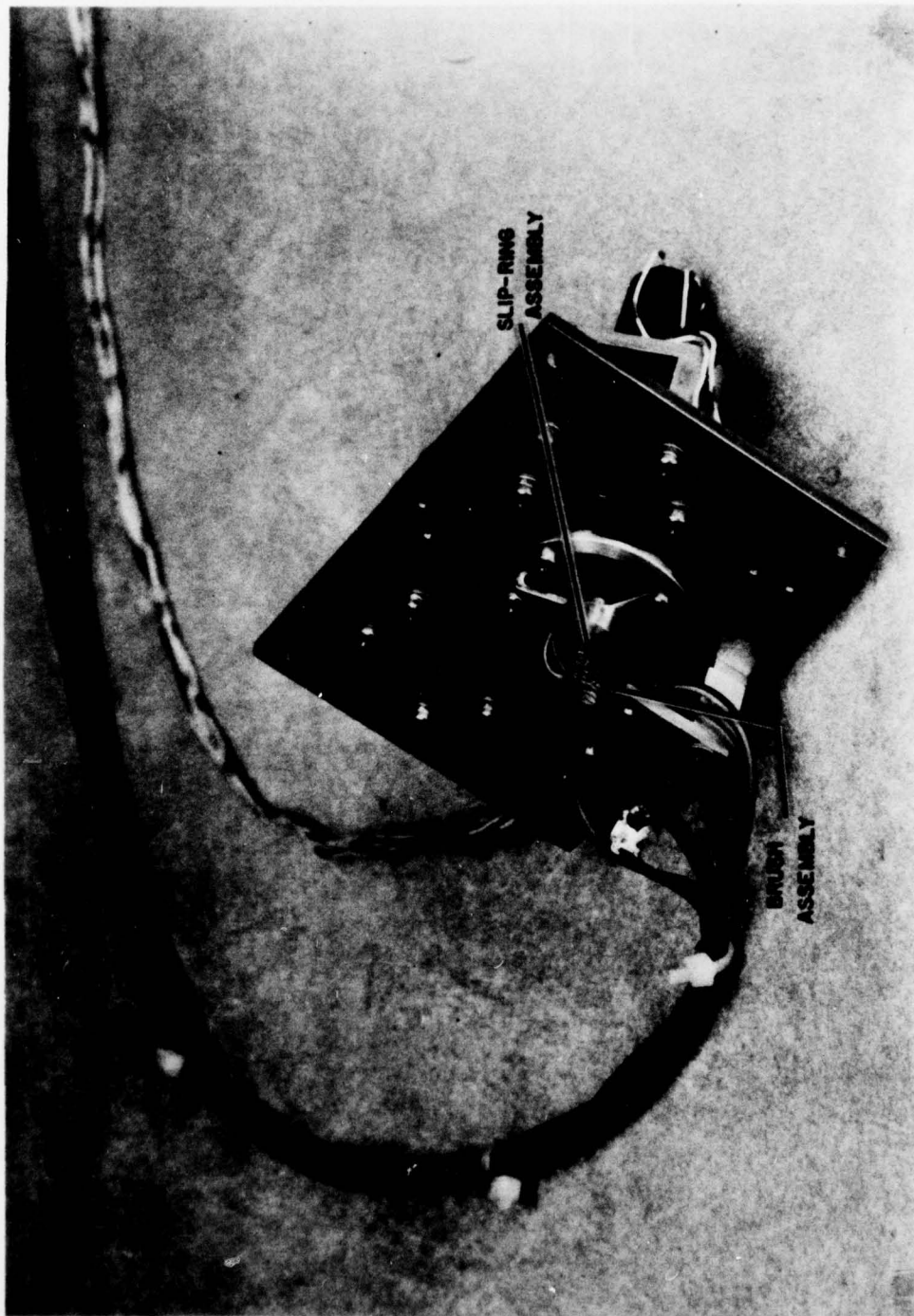


Figure 7. Array mount slip-ring assembly.

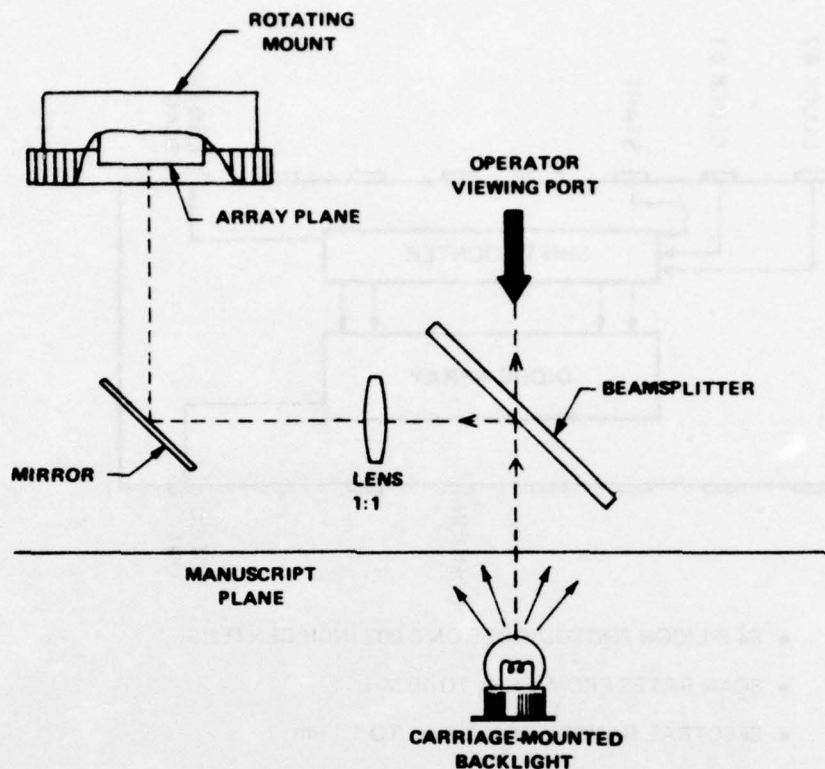


Figure 8. Basic optical configuration for the aided-track cursor.

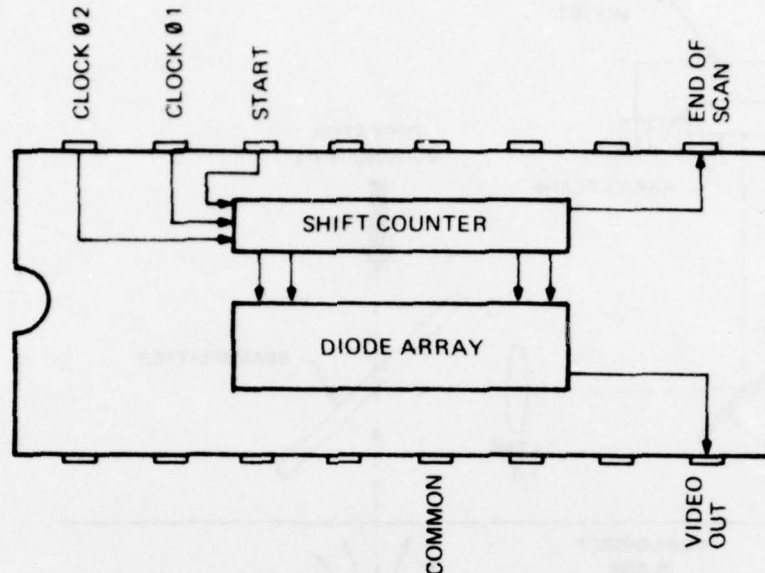
The heart of the system, the photosensitive linear array, is a 64-element unit manufactured by Reticon Corporation. Operational specifications and the functional blocks contained on the integrated circuit chip are shown in Figure 9. This array, representative of a number presently marketed, is available on an off-the-shelf basis.

2. Overall Aided-Track Cursor System

a. General

Figure 10 shows in block diagram form the system elements in terms of physical functional modules. As seen, the modules are:

- 1) Integral Aided-Track Cursor Unit. This unit contains the array and phase drivers, array mount, motor and feedback potentiometer, and the optical system, as discussed previously. This housing is simply attached to any existing cursor by a set of capture screws, so that it can be used interchangeably. An alignment procedure (Section VI.D) permits the crosshair center and the array rotational center to be measured and brought into correspondence.



- 64 SILICON PHOTODIODES ON 0.002 INCH CENTERS
- SCAN RATES FROM 1 KHz TO 10 MHz
- SPECTRAL RANGE FROM 0.4 μm TO 1.1 μm
- SATURATION EXPOSURE 0.8 $\mu\text{W-S/CM}^2$

Figure 9. Reticon RL-64.

- 2) Servo Module. The servo module shown contains the D/A converter to generate an analog signal from the computer-generated angular position, stabilization, gain, and motor drive amplifiers. In addition, an oscillator (120 Hz) is incorporated into this module to provide dither to the motor to overcome stictional levels for small angular signals. The feedback voltage is adjusted to provide for ± 512 degrees of rotation. The scale factor was chosen to correspond to the least significant bit of the 10-bit D/A converter or

$$\text{Scale Factor} = \frac{1024 \text{ degrees}}{20 \text{ volts}} = 51.2 \text{ degrees per volt}$$

- 3) Video Control Module. This module contains the array clock and the electronic functions for array scan control and generation of array phase voltages. It also contains a charge amplifier for amplifying array output signals. The boards performing these functions are purchased from Reticon for use with their array. A provision for synchronizing the scan start to the Gradicon output instant was made, but this mode, as will be pointed out, is not used.

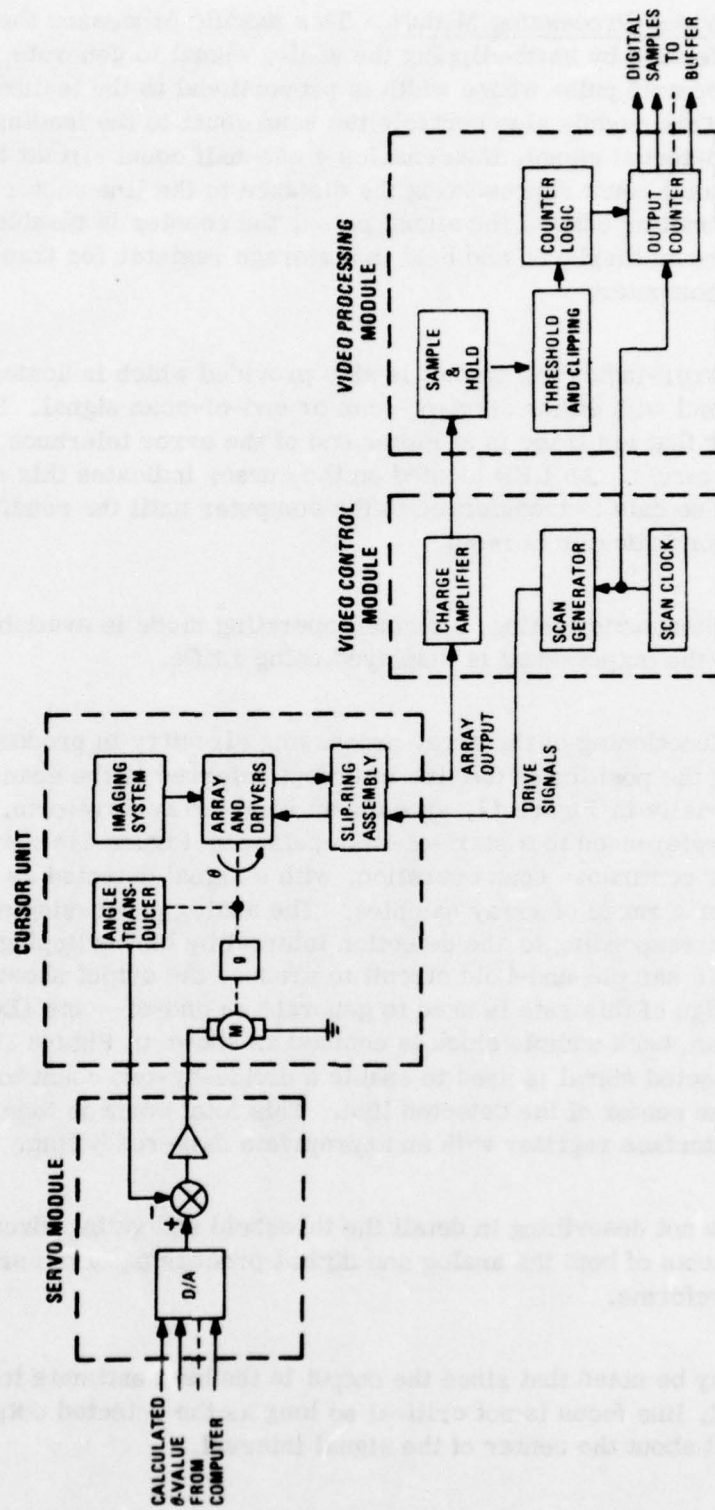


Figure 10. Block diagram of the aided-track cursor system showing functional units.

- 4) Video Processing Module. This module processes the detected feature by hard-clipping the analog signal to generate a count control pulse whose width is proportional to the feature line width. This module also controls the scan count to the leading edge of the detected signal, then enables a one-half count circuit to produce a total count representing the distance to the line center. At the trailing edge of the signal pulse, the counter is disabled, and the count displayed and held in a storage register for transfer to the computer.

An error-indicating circuit is also provided which indicates an overlap of the detected signal with either start-of-scan or end-of-scan signal. This indicator shows the operator that his trace is at either end of the error tolerance allowed within the aided-track circle. An LED located on the cursor indicates this condition. When this occurs, no data is transferred to the computer until the condition is corrected and the error indicator is reset.

For diagnostic testing, a manual operating mode is available by an internal switch, and the output count is displayed using LEDs.

The functioning of the array processing circuitry in producing an output count representing the position of the line intercept referred to the scan start element is described pictorially in Figure 11, showing an ideal array waveform. Basic timing relationships are referenced to a start-of-scan pulse; in Figure 11a the array chip output is shown for continuous scan operation, with a signal detected as shown by the reduced output over a range of array samples. The analog processing essentially produces a gate corresponding to the detection interval by hard-clipping the detected output from a sample-and-hold circuit to produce the output shown in Figure 11b; the trailing edge of this gate is used to generate an end-of-count (EOC) signal. At the start-of-scan, each sample clock is counted as shown in Figure 11c. The leading edge of the detected signal is used to enable a divide-by-two count to obtain the best estimate to the center of the detected line. This total count is then transferred to the computer interface register with an appropriate data-ready flag.

While not describing in detail the threshold and gating circuitry, all of the essential elements of both the analog and digital processing of the array output are given by these waveforms.

It may be noted that since the output is the best estimate to the center of the detected signal, line focus is not critical so long as the detected output is relatively symmetrical about the center of the signal interval.

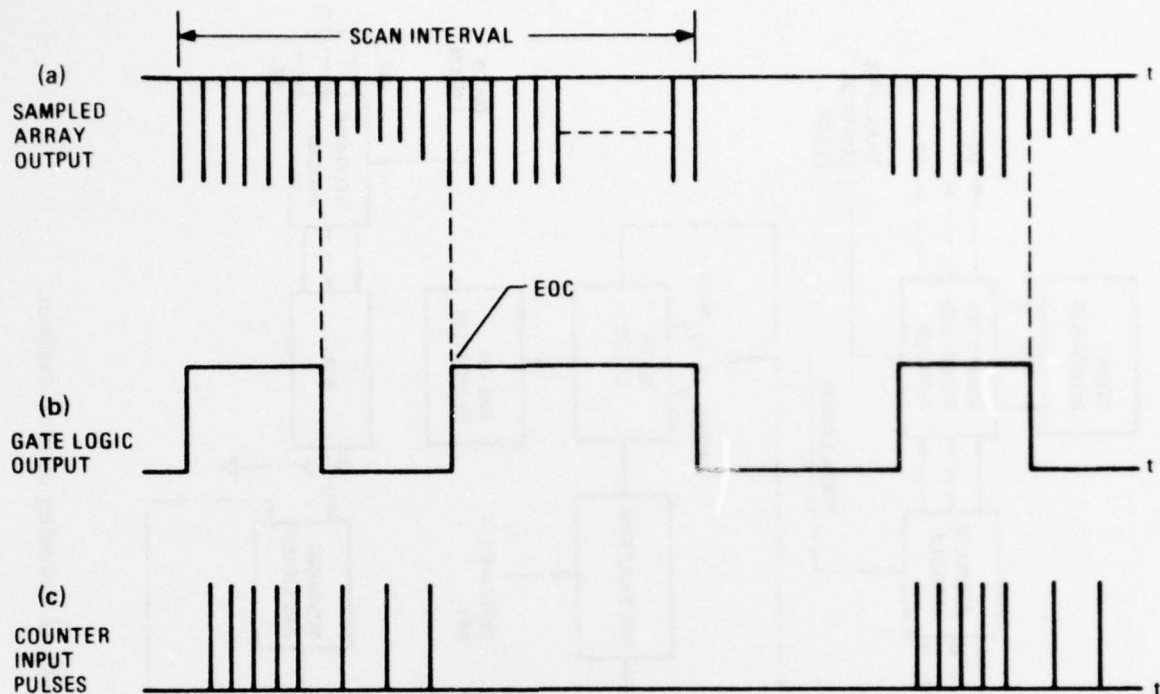


Figure 11. Output waveform diagrams. Gate logic generates signal for counting at half the array clock rate to define center of detected line.

Using the same line of reasoning, changes in depth of signal modulation with line width will not influence the accuracy of the count, assuming that the detected signal is above the threshold level.

Figure 12 provides further details of the functional units discussed. The following section describes the operation of the processing portion of the systems at a component level.

b. Circuit Description

1) Analog Processing

Analog processing of the array output is shown functionally in Figure 13. The main design objective of this portion of the system is to provide an unambiguous detection gate indication for count control, and for suppression of noise stemming from the sampling process and spatial variations in array illumination by thresholding.

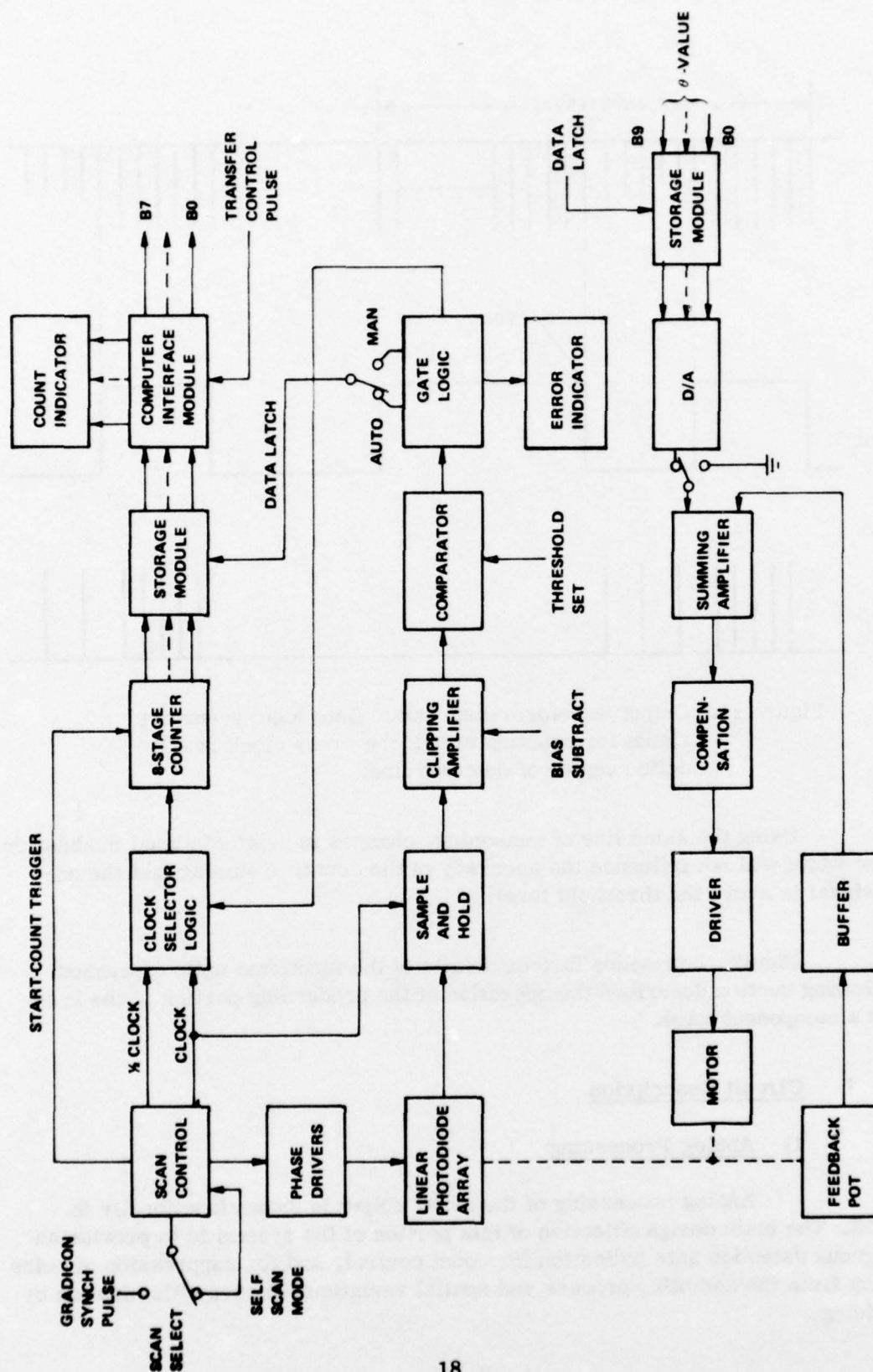


Figure 12. Overall block diagram of scanning cursor system.

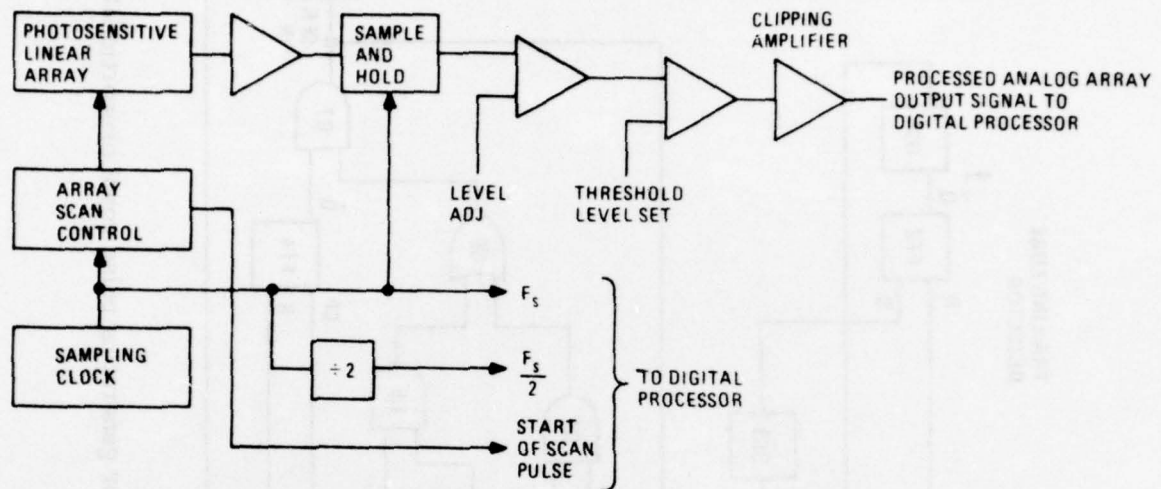


Figure 13. Array output analog processing.

Changes in light level or sample integration times are accommodated by the level adjustment shown. The clipping amplifier provides an output range compatible to TTL-logic circuitry.

2) Digital Processing

A functional description of the output digital processing follows with reference to Figure 14. The duration of the start-of-scan (SOS) pulse generated by the scan control circuits is extended to overlap the time at which the first array element sample occurs. This stretching is done by the variable one-shot (OS) shown, OS1. By this overlap, the initial negative going array output is inhibited from triggering flip-flop FF2 at scan start and prevents generation of false reset pulses by OS4. By having the duration of the SOS pulse controllable, any element can be chosen as the reference elements from which the count is started.

The analog processed signal is gated to the digital processor at the end of the stretched start-of-scan pulse by gates G1 and G2. At start-of-scan, counter C1 is also cleared. When the delayed start-of-scan ends, the counter starts

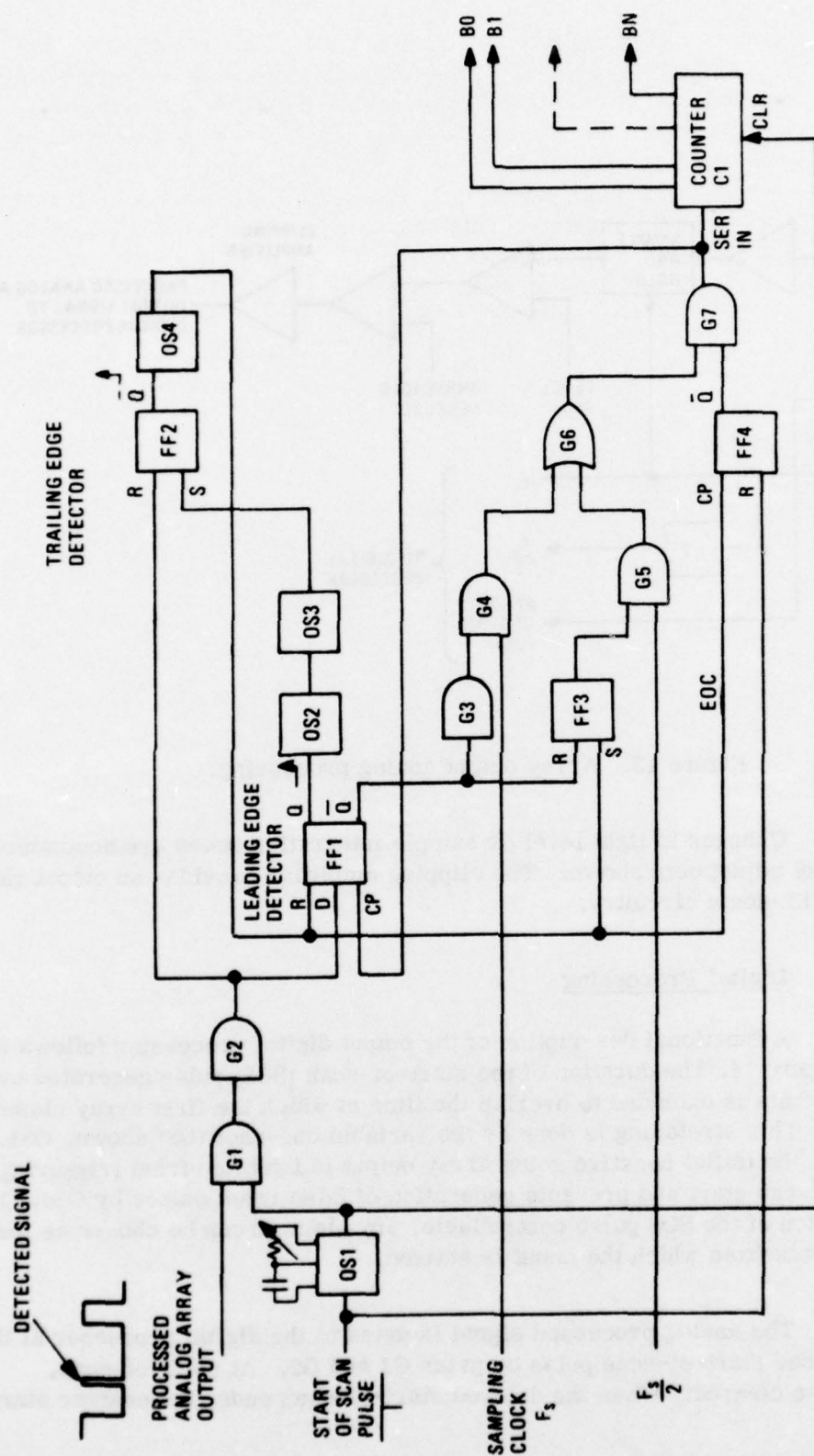


Figure 14. Digital array output processor for generating pulse count proportional to center of detected signal.

counting the array sampling clock, F_s , through an enabled gate, G4, and an OR circuit, G6. The counter input gate, G7, is also enabled at start-of-scan by a reset signal. When the detection gate occurs, the data input of FF1 changes state; this state is transferred to the output on the next sampling pulse via the CP-input of FF1. At this time, the FF1 output disables the direct sampling clock gate, G4, while enabling the half frequency $F_s/2$ clock gate, G5, by the state change of FF3. The half-frequency clock pulses are then counted. This half-count, which results in a count representing the center of the signal detection interval, continues until the trailing edge of the detection gate signal occurs. The output of FF1 is also used to condition the trailing edge detector composed by FF2 and OS4. This conditioning occurs when the leading edge of the signal is detected by FF1. The change in state of FF1 produces a pulse at the output of OS2 which is delayed in time by OS3. The delay prevents unwanted resets of FF2 due to uncertainties on the leading edge of the detected signal. When the trailing edge occurs after the conditioning, a change of state of FF2 results in an output pulse from OS4. Further counting is prevented at this time by disabling the counter input gate, G7, via FF4 whose state is changed by the output pulse of OS4; this pulse also resets FF1 and FF3 to their initial states. The counter output, represented by output bits B0 through BN, is held until the next start-of-scan pulse occurs, which clears the counter. During this interval, it can be transferred out via an interface.

This describes the complete counting cycle, which is repeated for each array scan.

Section III

ERROR ANALYSIS

A. TRACKING VELOCITY CONSIDERATIONS

Design objectives were to provide for a correctional accuracy corresponding to ± 1 resolution element of the array, which for the array chosen is ± 2 mils. In order to realize this accuracy, a tradeoff must be made between maximum tracking speed and an array integration time which results in a signal level ensuring consistent detection. Gradicon outputs in the incremental mode are generated when cursor motion in X or Y direction is in the order of 0.010 inch (10 mils). For maximum tracing velocity, an array output must be obtained before motion of 0.002 inch is exceeded after the Gradicon output. Experimentally, a 25-kHz array scan rate gives an adequate integration time. Although the array used is 64 elements in length at 0.002 inch pitch, only 33 elements are actively employed in detecting feature intercepts to allow for minimum interference in tracing closely spaced features. However, time must be allowed for the scan of at least 64 elements plus an additional 8-element interval to allow for a reset interval.

The maximum allowable tracing velocity for obtaining an array output within one array resolution element of motion is given by

$$v = \frac{R}{N} T_s$$

R = resolution element = 0.002 inch

N = effective elements scanned = 72 scans

T_s = array scan frequency = 25,000 scans per second

For the numerical values given, the maximum velocity is then limited to 0.7 in/s.

The tolerance given to the operator in tracing the feature lies within an aided-track circle of 0.064 inch (approximately 1/16 inch).

Further, based on considerations of typical manuscripts, line detection must be achievable over line widths ranging from 4 to 20 mils.

B. ALIGNMENT CONSIDERATIONS

The rotational mount for the photodiode array is maintained positionally by a three-point ball-bearing suspension system. Two alignments must be considered to preserve the accuracy capabilities of the aided-track cursor; first, the rotational axis

of the array cannot vary beyond one resolution element (± 0.001 inch), and, second, the center of the aided-track viewing circle should be optically aligned to correspond to the center element of the active scan output. Most stringent is the first requirement, and it has been readily achieved in the feasibility model. The mechanical alignment of the center of rotation of the array mount has been measured under a toolmaker's microscope to be within ± 1 mil, or $\pm \frac{1}{2}$ resolution element.

The optical alignment is of less significance because any constant offset can be accounted for in computer algorithms used in calculating the correctional factor. (See Section VI.D for a discussion of alignment techniques using the array output to measure center offsets.)

C. ROTATIONAL ERRORS

Because of the small dimensions involved in the correctional factors, errors due to rotational position inaccuracies are at worst one resolution element for the case of a 7-degree error in tracing an extreme curvature represented by radius equal to that of the aided-track circle. Design provisions have been made for computer-correction of rotational errors by an additional I/O interface which provides the computer with actual array rotational values in response to commands. Need for this additional interface is to be established during evaluational testing.

D. PHOTOMETRIC NOISE

In addition to errors which can be allocated to mechanical and optical alignment sources, the dominant error source stems from spurious detections from non-uniform illumination and artifacts generated by tolerance-circle intercepts and any sizable manuscript imperfections such as dirt particles. Spatial noise caused by illumination non-uniformity remains invariant since the light source travels with the cursor.

These noise sources are not of significance if they are below the system threshold level set for noise rejection.

E. PROCESSING ERROR

Uncertainties in the detection and conversion of the signal to a binary count are inherent to all processors, even in noiseless systems. Detection uncertainty is a result of quantizing the output signal in the sample-and-hold process, and can be represented by a worst case ± 1 count error.

F. COMPUTER APPROXIMATION ERROR

In the discussion of software, it is pointed out that the Gradicon encoders are calibrated in the basic unit of 20 micrometers per count, while the array output count is doubled to represent 1 mil per count. A scale factor is introduced in the computer program to convert array pulse count to a corresponding Gradicon count. This conversion can result in a 1 count error in the value of the array data transferred to the computer, or ± 0.5 mil.

Table 1 summarizes the contribution of each error source for worst case error. Two conditions are shown: the first column assumes maximum tracing rate of 0.7 in/s and maximum angular error of 7 degrees; the second column is given for the case where tracing velocities are well below the maximum allowable rate and angular errors contributing negligible effect on the array output count. Count errors given in the table are referred to the array resolution of 2 mils.

It is assumed that noise is below threshold and that offsets have been compensated in the computer algorithm.

While systematic errors, i.e., cyclic errors due to rotational offsets, are included in this estimate, known repeatable cyclic errors are also subject to computer correction, given increased algorithm complexity and adequate computer capability.

TABLE 1. TABULATION OF WORST-CASE SYSTEM ERROR IN THE CORRECTED COORDINATE VALUE

Error Source	Count Error*	
	Worst Case**	Typical Worst Case
Tracking velocity	± 1	-
Rotational alignment	$\pm \frac{1}{2}$	$\pm \frac{1}{2}$
Angular error	± 1	-
Processing uncertainty	± 1	± 1
Computer approximation	$\pm \frac{1}{2}$	$\pm \frac{1}{2}$
Total	± 4	± 2

*Referred to array resolution element of 0.002 inch.

**At maximum tracing rate of 0.7 in/s and 7-degree angular error in tracing curvature equal to array radius.

The worst-case error of ± 4 counts at the design limits represents a conversion error of ± 8 mils, while the typical reading uncertainty is ± 4 mils, worst case. On a statistical basis, the probability that the error is ± 1 mil or less is 0.5. Computer errors due to metric conversion factors were not initially anticipated, since the Gradicon was understood to be calibrated in English units, i.e., counts/inch. This approximation error can be reduced to arbitrarily small levels by increasing the computer conversion accuracy for a total typical uncertainty of $\pm 3\frac{1}{2}$ mils.

Section IV

COMPUTER INTERFACE

The following paragraphs refer to computer modifications which were made to permit addition of two peripheral input channels and one output channel. All channels have a 16-bit capacity. While these channels were added specifically for this program, they are not restricted to this use; i.e., if future developmental concepts require data manipulations from any peripheral devices, these input/output channels can be employed by observing the instructions in the Hardware User's Description, presented on the next page.

Addition of these interfaces does not affect normal station operation of this computer in its performance as a video terminal station for the Gradicon digitizing table.

HARDWARE USER'S DESCRIPTION - RCA SPECIAL INTERFACES

(SERIAL #198)

PHYSICAL:

These 3 interfaces (θ , ρ , and θ -raw)* are located on the CPU backplane. There are 4 cards associated with these interfaces. The θ -interface is in slot 309, the ρ -interface in slot 306, and the θ -raw interface in slot 307. Slot 315 contains a 150-wire cable card terminating the cable between the Gradicon terminal box, and the 3 interfaces. The terminal box provided interfaces Imlac's cable to RCA's cables.

ELECTRICAL:

All 3 interfaces are 16-bit parallel interfaces. The ρ and θ -raw interfaces transfer 16 bit (ρ and θ -raw) words into the PDS accumulator using either skip or interrupt programming. The θ -interface transfers a 16-bit θ word from the PDS to the Gradicon servo D-A latches.

The θ -raw and ρ input lines are terminated with 470 Ω pull-ups and latched by 7475's.

The θ lines are driven by 7403's, and should be terminated with 470 Ω pullups. The θ -write strobe and grad ready flag are driven by a 7438. A 150 Ω pull-up is recommended for these terminations.

I θ -INTERFACE: Issuing an IOT 712 transfers the contents of the Imlac accumulator bits 5-15 to the latches of the Servo D-A.

II ρ -INTERFACE: Issuing an IOT 711 transfers the complement of Gradicon ρ -word into the 8 LSB's (8-15) of the Imlac accumulator. Bit 14 in the status word is assigned to the ρ -ready flag. The status word may be read into the Imlac accumulator with IOT 102. IOT 704 causes the next instruction to be skipped if the ρ flag is high. If the interrupts are armed and enabled, a first level interrupt will be generated when this flag goes high. This device's interrupt will be armed by issuing IOT 142 with bit 14 in the Imlac accumulator set.

III θ -raw-INTERFACE: IOT 701 transfers the 10-bit θ -raw word into the 10 LSB's of the Imlac accumulator. Bit 13 is the status bit for this flag; IOT 714 causes the next instruction to be skipped if the θ -raw flag is high. First level interrupts can be generated off this flag if the interrupts are armed with bit 13 in the accumulator set, and interrupts are enabled.

IV Both the ρ -flag and the θ -raw flag may be cleared by issuing IOT 702.

V INSTRUCTION SUMMARY: Bit 14- ρ status bit. Bit 13 θ -raw status bit.

* θ and ρ have been defined in previous sections as angular position of the array and intercept distance, respectively. θ -raw is the servo potentiometer reading converted to digital form to indicate to the computer actual versus commanded positions to derive corrective factors. It is not anticipated that the θ -raw output will be required.

IOT 142 Arm Interrupts - This IOT arms all (word 2, level 1) interrupts whose status bits are set.

IOT 102 Read Status word - This IOT reads the IO device flags into the Imlac accumulator.

IOT 712 Write Θ -value - This IOT transfers the contents of the accumulator to the Gradicon Θ -latches.

IOT 711 Read ρ -value - This IOT transfers the Gradicon ρ -value to the Imlac accumulator.

IOT 701 Read Θ -raw-value - This IOT transfers the Gradicon Θ -raw value to the Imlac accumulator.

IOT 704 Skip if ρ flag set - This IOT causes the next instruction to be skipped if ρ data is ready.

IOT 714 Skip if Θ -raw-flag set - This IOT causes the next instruction to be skipped if Θ -raw data is ready.

IOT 702 Clear flags - This IOT clears the ρ and Θ -raw flags.

Section V

SOFTWARE FOR THE SCANNING CURSOR

A. GENERAL

Two computer programs were written for the PDS-1D to demonstrate the correcting capability of the scanning cursor. Both programs contain the basic algorithm necessary for the operation of the scanning cursor. The basic algorithm is flow charted in Figure 15. The difference is the method of displaying the output. The program titled "Scanning Cursor Plot Curves" displays on the screen of the PDS-1D the feature as it is being traced and corrected.

The program titled "Scanning Cursor Display Digits" displays numerical data on the screen of the PDS-1D. The first line of data to be displayed consists of the first pair of coordinates (X, Y) with X corrected, the ρ -count for the second pair of coordinates, the second pair of coordinates (x, y) with x corrected, and the initial angle of rotation of the array. The angle of rotation is a number from 0 to 1023 with one count equal to one degree. The array is parallel to the X-axis and scans left to right when the angle is 512. The array can rotate almost three revolutions, allowing closed contours to be traced. Subsequent lines contain sample number, the X and Y coordinates as read from the Gradicon, the ρ -count from the array, the corrected X and Y coordinates, and the angle of rotation of the array. Up to 20 lines of data may be displayed. The data is scrolled down one line as each new data point is read and processed.

The programs were debugged and several modifications were patched into the object tapes. The listings for these two programs, the modified object tapes, and a list of the modifications are available. The listings included in this report are source listings containing the modifications made above, but have not been assembled to assure their accuracy because of the expiration of the RCA contract. Other modifications are necessary, depending on the resolution setting on the Gradicon and the desired output resolution. The modifications are outlined in Tables 2 and 3.

B. OPERATION OF THE SCANNING CURSOR

The scanning cursor can operate with the Gradicon in either the point mode or the increment mode. The software is limited such that the Gradicon must be set so that the feature to be traced lies in the first quadrant; i.e., X and Y as read from the Gradicon must be positive. Operate with the Gradicon INC switch =2 and resolution 2, 4, or 8. In resolutions 2, 4 and 8, one count from the Gradicon equals 20, 40 and 80 micrometers, respectively. The data is scaled so that one count equals 20 micrometers at all resolutions when the program is modified as outlined in Tables 2 and 3.

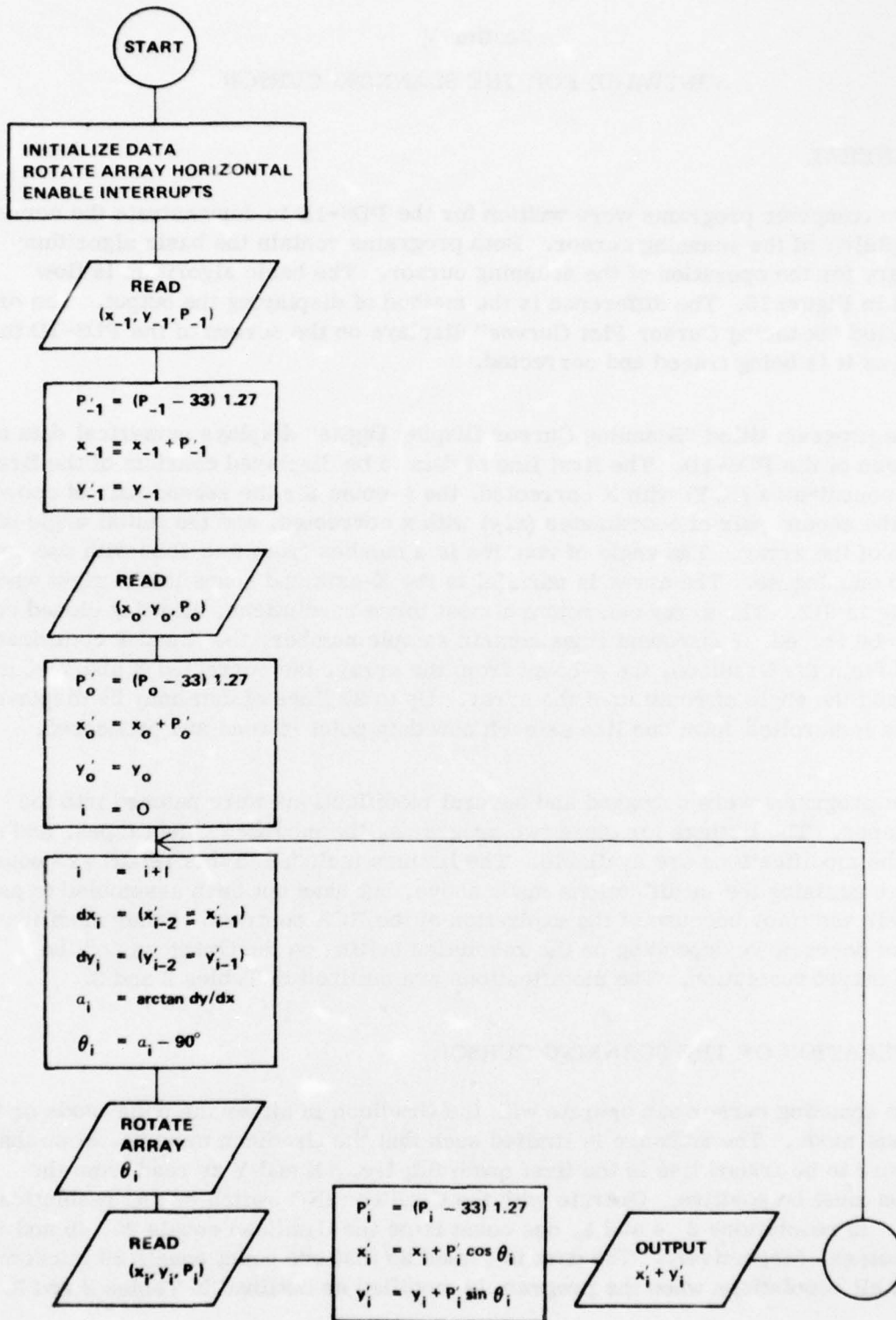


Figure 15. Logic diagram.

TABLE 2. MODIFICATIONS FOR SCANNING CURSOR DISPLAY DIGITS

Line of Listing	Res 2		Res 4		Res 8	
	MNEMONIC	Octal Code	MNEMONIC	Octal Code	MNEMONIC	Octal Code
361	MXI: Dec 8	000010	MXI: Dec 8	000010	MXI: Dec 8	000010
496	NOP	100000	SAL 1	003041	SAL 2	003042
499	NOP	100000	SAL 1	003041	SAL 2	003042

TABLE 3. MODIFICATIONS FOR SCANNING CURSOR PLOT CURVES

Line of Listing	Res 2		Res 4		Res 8	
	MNEMONIC	Octal Code	MNEMONIC	Octal Code	MNEMONIC	Octal Code
322*	MXI: Dec 8	000010				
426	NOP	100000	SAL 1	003041	SAL 2	003042
429	NOP	100000	SAL 1	003041	SAL 2	003042
636**	SAL 2	003042	SAL 2	003042	SAL 2	003042
651**	SAL 2	003042	SAL 2	003042	SAL 2	003042
694**	CPI2:1	000001	CPI2:1	000001	CPI2:1	000001

*MXI is the number of counts (20 micrometers/count) by which X or Y must change before the coordinate (X, Y) is used. Reduce MXI for greater resolution.

**Scale the number of counts in X and Y before displaying feature on screen. The number of counts to produce one increment on screen = 2 x CPI2.

The linear array of sensors effectively consists of 33 two-mil elements. The output from the array is the sum of the position numbers of the first and last elements which are obscured by the feature. An error light in the cursor indicates when the feature is outside the 1/16 inch reticle. The effective output from the array is a count between 10 and 66 where 1 count equals 1 mil. The array was optically aligned so that a count of 33 represents the center of the array; however, this count may be adjusted to correct for an offset. Thus ($P-33$) is the distance from the center of the cursor to the feature measured along the array. This distance is scaled by 1.27 in a table look-up so that 1 count equals 20 micrometers, the same units as X and Y from the Gradi-con.

$$P'_i = 1.27 (P_i - 33) \quad i = -1, 0, 1, \dots \quad (1)$$

The scanning cursor operates as follows (see footnote 1). The array is initially rotated so that it is parallel to the X-axis and scans left to right. This is undesirable if the initial segment of the feature to be traced is also parallel to the X-axis. In this case the algorithm should be modified to begin with the array in a vertical position.

Read two points and the corresponding values, (X_{-1}, Y_{-1}, P_{-1}) and (X_0, Y_0, P_0) with the array parallel to the X-axis (see Figure 16). In the increment mode the Gradicon samples whenever X or Y changes by two times the resolution (INC=2). Changing the variable MXI in the program allows an even coarser sampling to be used by the program (see Tables 2 and 3). In the point mode the foot pedal must be operated to sample. Compute the corrected X and Y coordinates from Equations 2 and 3, which are special cases of Equations 8 and 9, respectively:

$$X'_i = X_i + P_i \quad i = -1, 0 \quad (2)$$

$$Y'_i = Y_i \quad \text{array parallel to X-axis} \quad (3)$$

If the array were initially parallel to the Y-axis, Equations 2 and 3 become:

$$X'_i = X_i \quad i = -1, 0 \quad (4)$$

$$Y'_i = Y_i + P_i \quad \text{array parallel to Y-axis} \quad (5)$$

Compute the slope of the line from (X_{-1}, Y_{-1}) to (X_0, Y_0) with $i = 1$ in Equation 6:

$$\alpha_i = \arctan \frac{Y'_{i-1} - Y'_{i-2}}{X'_{i-1} - X'_{i-2}} \quad i = 1, 2, \dots \quad (6)$$

Footnote 1. Obtaining the initial angular orientation of the array can be more simply determined following procedures given in Section VI. E. In this procedure initial orientation of array angle and feature angle is not dependent on determining the required array orientation.

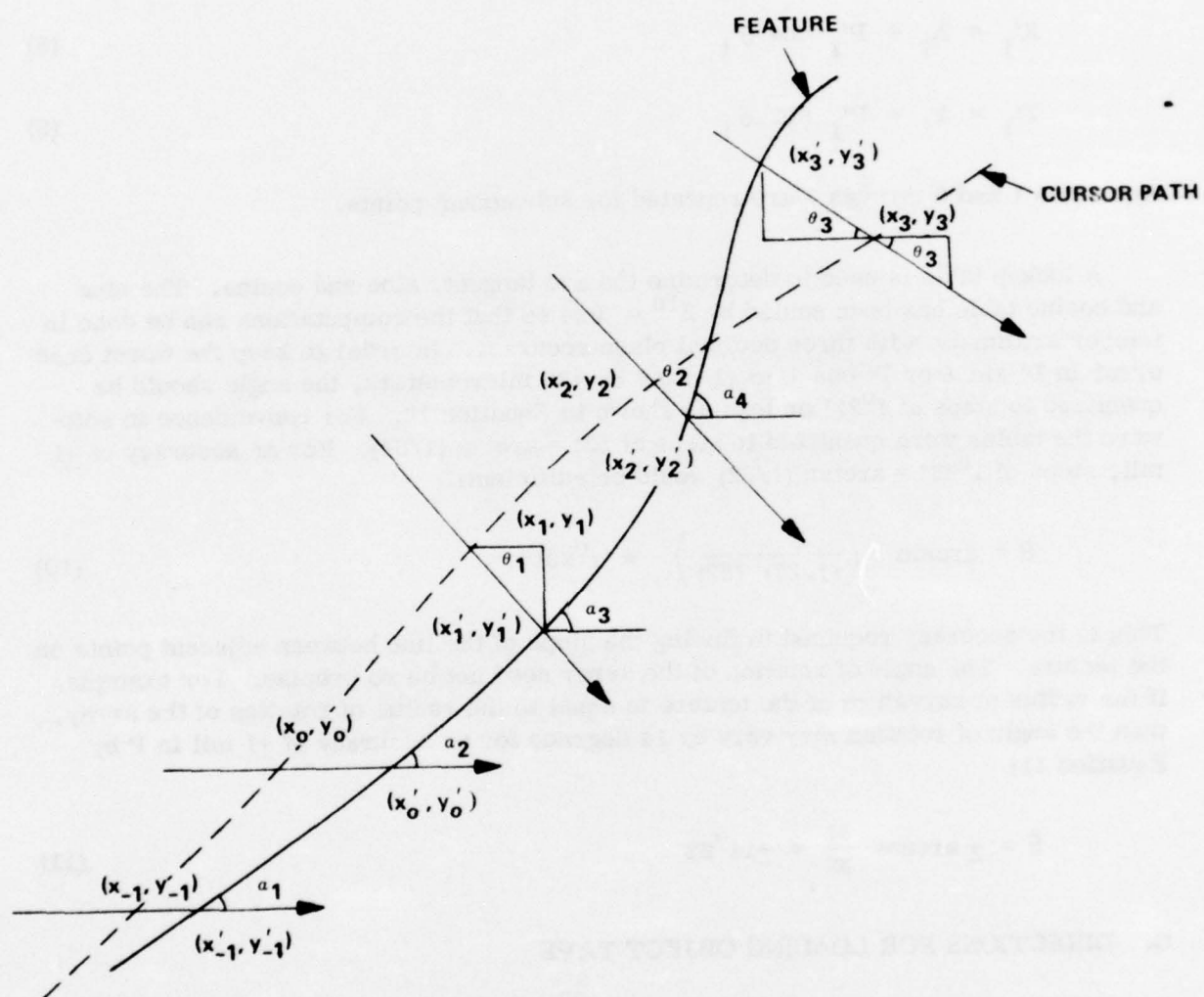


Figure 16. The path of the cursor, showing corrections.

Rotate the array through the smallest angle θ_i such that it will be perpendicular to the line from (X'_{i-2}, Y'_{i-2}) to (X'_{i-1}, Y'_{i-1}) :

$$\theta_i = \alpha_i - 90^\circ \quad \text{for } i = 1, 2, \dots \quad (7)$$

Read the next pair of coordinates (X_i, Y_i) and the corresponding P_i and compute the corrected coordinates from Equations 1, 8 and 9:

$$X'_i = X_i + P'_i \cos \theta_i \quad (8)$$

$$Y'_i = Y_i + P'_i \sin \theta_i \quad (9)$$

Equations 1 and 6 through 9 are repeated for subsequent points.

A lookup table is used to determine the arc tangent, sine and cosine. The sine and cosine table has been scaled by $2^{10} = 1024$ so that the computations can be done in integer arithmetic with three decimal place accuracy. In order to keep the worst case error in $P' \sin \theta$ or $P' \cos \theta$ to ± 1 count or ± 20 micrometers, the angle should be quantized to steps of $1^\circ 23'$ or less as shown in Equation 10. For convenience in software the tables were quantized in steps of $53' = \arctan(1/64)$. For an accuracy of ± 1 mil, steps of $1^\circ 47' = \arctan(1/32)$ would be sufficient:

$$\theta = \arcsin \left(\frac{1}{(1.27)(32)} \right) = 1^\circ 23' \quad (10)$$

This is the accuracy required in finding the slope of the line between adjacent points on the feature. The angle of rotation of the array need not be so precise. For example, if the radius of curvature of the feature is equal to the radius of rotation of the array, then the angle of rotation may vary by 14 degrees for an accuracy of ± 1 mil in P by Equation 11:

$$\theta = \pm \arccos \frac{31}{32} = \pm 14^\circ 22' \quad (11)$$

C. DIRECTIONS FOR LOADING OBJECT TAPE

- 1) Turn power on to PDS-1D and Paper Tape Reader (PTR).
- 2) Press stop on console.
- 3) Load object tape in PTR.
- 4) Set address switches on console to 40_8 .

- 5) Press start on console.
- 6) After tape has been read, set address switches to 100_8 .
- 7) Press start on console.
- 8) Begin cursor operation.
- 9) Restart at 100_8 in case of error.

Section VI

CONCLUSIONS AND RECOMMENDATIONS

A. PRELIMINARY TEST RESULTS

Because of contract expiration, evaluational testing of the complete system could not be undertaken.

While no full station evaluation was possible, preliminary tests using the cursor alone were carried out both at RADC and at the ATL facility at Camden, NJ. Since the gain and threshold must be adjusted for optimum performance with a given light source, only limited testing was performed at ATL. In general, source level and uniformity of the simulated Gradicon table at Camden were poorer than observed at RADC, and hence improved readings can be expected in an operational situation.

Signal width measurements showed that line widths from 5 mils to 20 mils produced consistent noise-free detection gates at the comparator output. This output is the counter control gate for estimating line centers. For these tests a 10-ms integration time was used, with an array sample rate of 15 kHz. The test medium was photographic lines on tracing vellum.

Typical outputs of the processing electronics are shown in Figure 17 and Figure 18.

These tests performed at RADC produced similar results, with good time stability.

While no dynamic testing of the array rotation servo was made, it has been demonstrated that it does respond to inputs as small as the least significant bit of the D/A converter (approximately 20 mV). A dither circuit was added to reduce stiction present, but its use may not be required.

Other observations made on-site include the fact that no interaction was noted between the Gradicon unit and the aided-track cursor assembly, indicating that no compromises in accuracy are made in processing data.

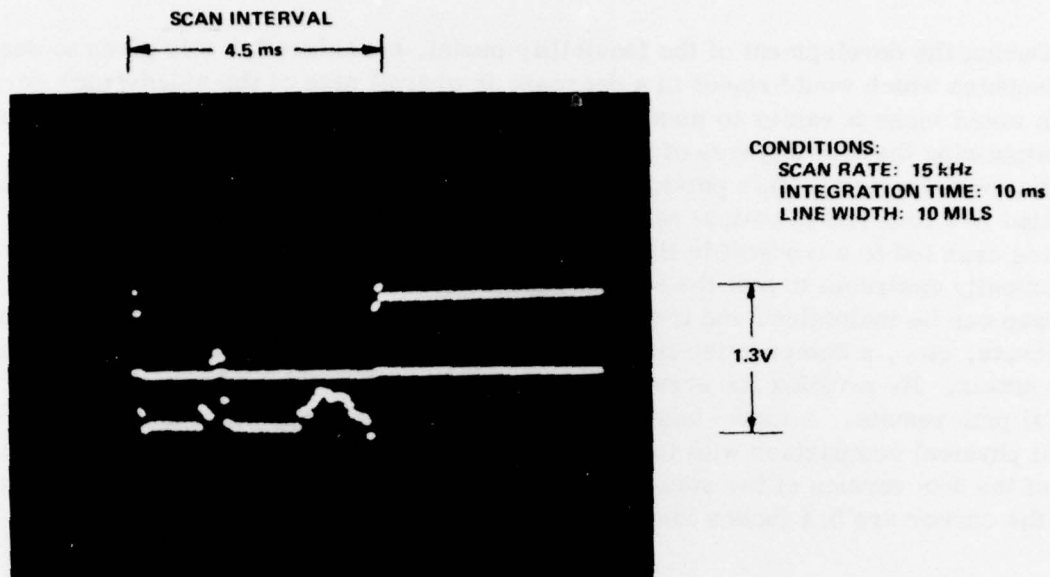


Figure 17. Sample-and-hold output with threshold level superimposed. Significant shading of the illumination is observable toward the end of the scan. Such shading determines the threshold setting.

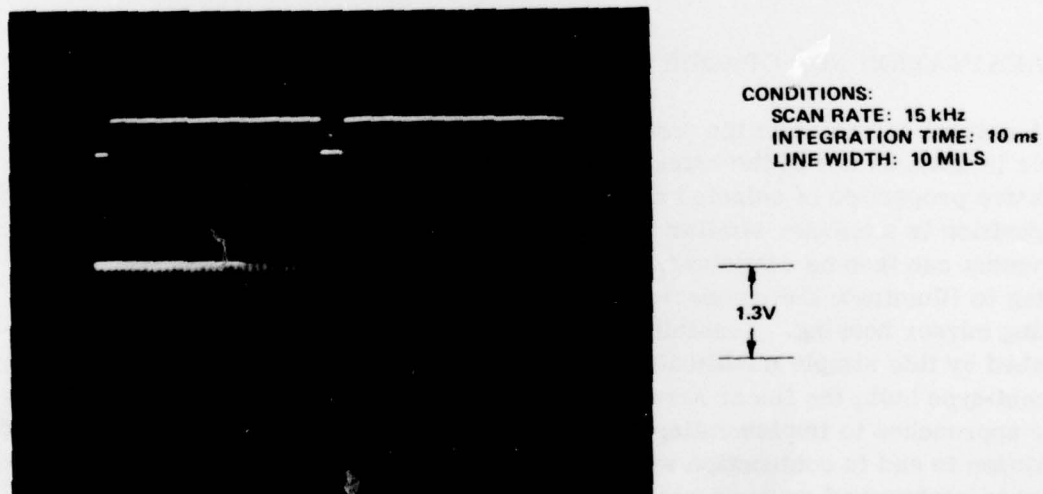


Figure 18. Array output pulses (bottom trace); signal gate generated at the comparator (top trace). This gate controls the count-by-two circuitry for estimating distance from scan start to the center of the line. Minor peaks seen are due to the aided-track reticle.

B. IMPROVED CURSOR CONFIGURATION

During the development of the feasibility model, consideration was given to design philosophies which would result in a decrease in overall size of the aided-track cursor which would make it easier to manipulate on the table. Original designs were aimed at maintaining the viewing area of the unmodified cursor contained within a 2-inch circular viewing port. This particular design goal fixed the dimensional limits and resulted in a long folded optical path. Reconsideration of the design based on the viewing area led to a tradeoff in this parameter. While a large viewing area is psychologically desirable in that the spatial relation of the traced feature with other features can be maintained and tracing motions can be adjusted to anticipate curvature, intercepts, etc., a compromise in this viewing area can result in a much more compact cursor. By revising the area to be contained in a 1-inch circle, a shortened optical path results. A model based on the 1-inch viewing port was constructed for an actual physical comparison with the feasibility model. Figure 19 shows the configuration of the new version of the cursor approximately to scale. The overall dimensions with the cursor are 5.4 inches long by 3.3 inches wide by 1.7 inches high.

The second-generation model, which was found to be significantly easier to handle than the feasibility model, would be the proposed configuration for future developmental types used for evaluation purposes.

Figure 20 and Figure 21 are photographs of the improved design cursor and the feasibility model, respectively, for comparison.

C. ADAPTATION FOR OPAQUE TABLE OPERATION

A natural extension of the photo-optical techniques used in construction of the cursor is towards use of the same instrument on opaque top digitizing tables. Use of reflective properties of selected manuscript media could prove feasible in detecting line position in a manner similar to that of the transmissive mode. A dual-purpose instrument can then be conceived. Positioning a light source(s) within the cursor housing to illuminate the manuscript would require only minor modification to the existing cursor housing. Feasibility of this operational mode should be quickly established by this simple modification. Initial illumination would be with a common filament-type bulb; the linear array has maximum sensitivity in the near-IR range. Other approaches to implementing a reflective mode of operation can be considered in addition to and in conjunction with this initial direct approach to provide for immunity to background sources which could affect operation.

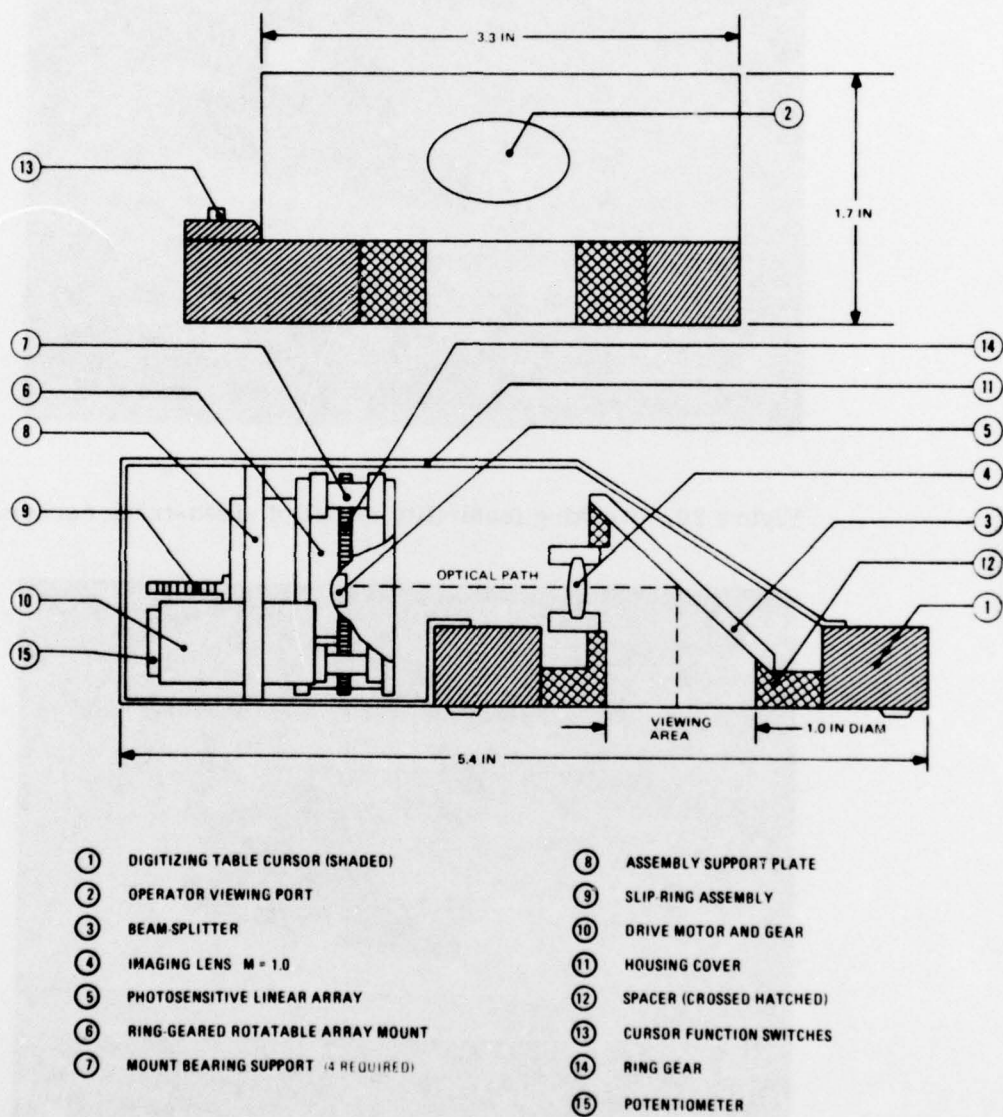


Figure 19. Mechanical configuration for improved version of the aided-track cursor.

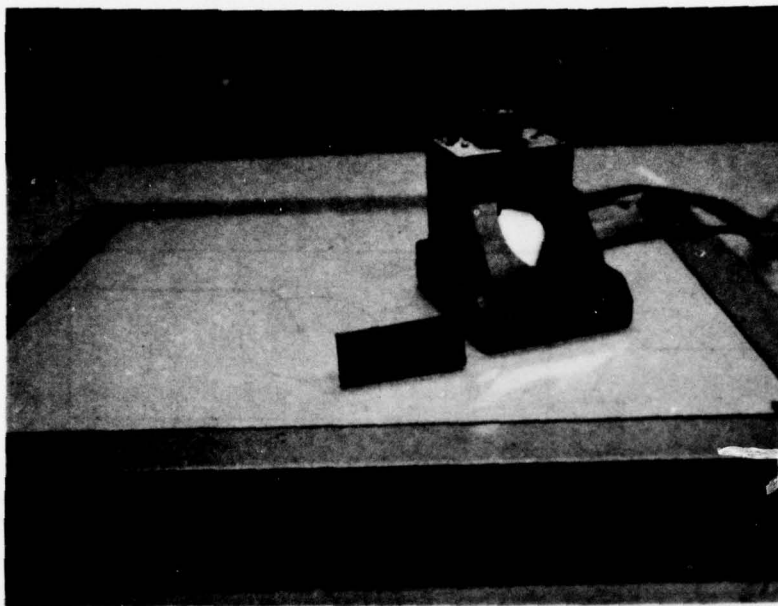


Figure 20. Working feasibility model of aided-track cursor.

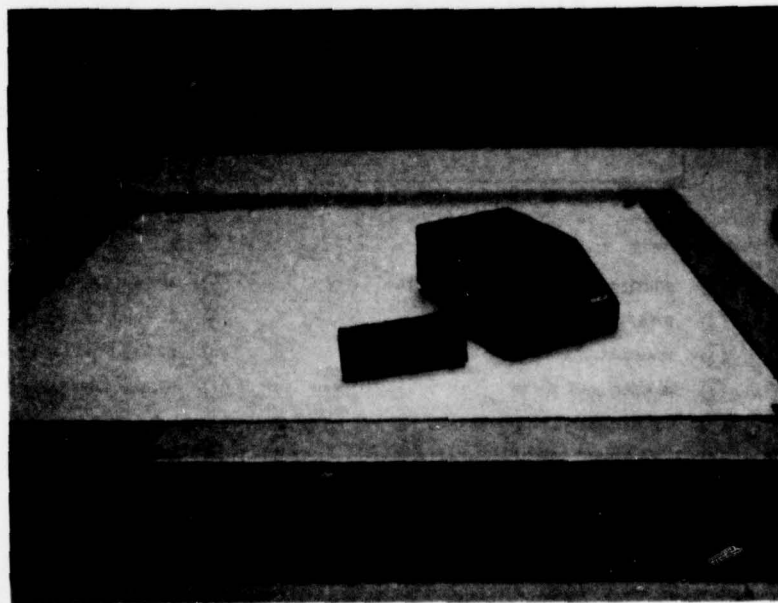


Figure 21. Proposed advanced developmental model of aided-track cursor.

Figures 22 and 23 show the configuration for a transmissive and a reflective detection system, respectively, as proposed for the improved design cursor. No changes are anticipated for the optical system, although some revision may be necessary electronically to account for a decreased signal range expected in the reflective mode. Primarily, new gain and threshold settings would be required.

D. ALTERNATE METHODS OF ARRAY ALIGNMENT

For cursor interchangeability, two procedures may be followed for taking into account offset distances which can exist from cursor to cursor between the array rotational center, and the cursor crosshair center. The first procedure would involve optical and mechanical alignment by viewing the projected array rotational center on the crosshair; the second procedure would determine the offset distance in X and Y electronically. In the first procedure the centers may be aligned by zeroing the electrically generated counts in X and Y by fine mechanical motions of the array housing; in the second method measured offset values can be used as correctional constants in a computer algorithm which accounts for the offset. Offset errors can be determined by providing a zero-degree and 90-degree reference position for the array use in conjunction with a reference X-Y coordinate line as demonstrated in Figure 24.

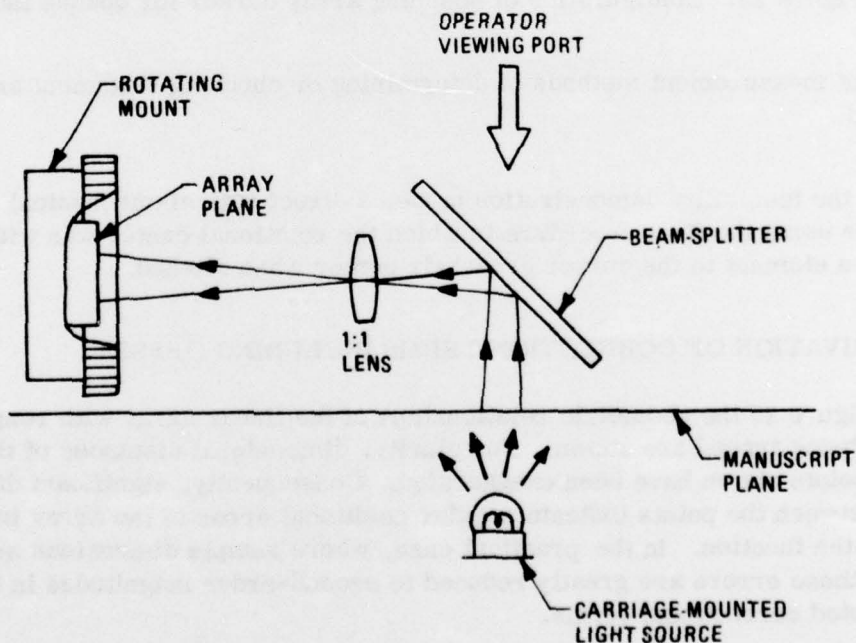


Figure 22. Configuration of a backlighted scanning array cursor.

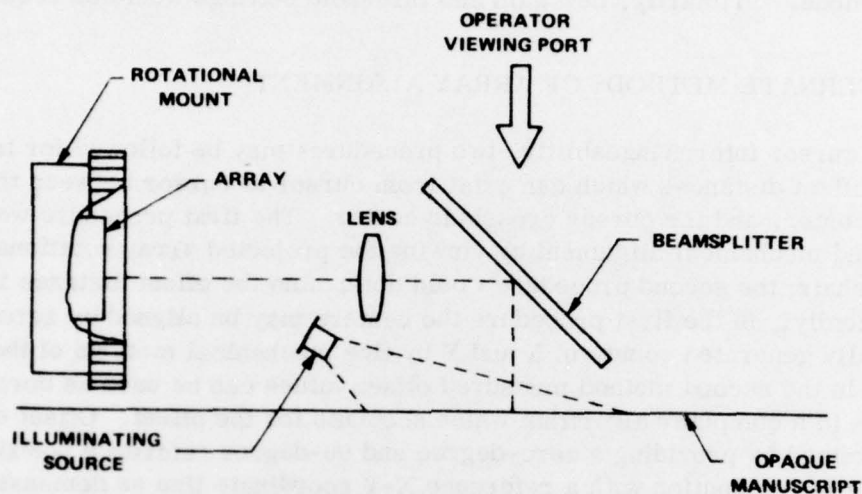


Figure 23. Configuration of scanning array cursor for opaque tables.

Count measurement methods of determining or checking alignment are to be evaluated.

For the feasibility demonstration mode, a direct optical-mechanical alignment was made using the first procedure in which the rotational center was within one resolution element to the cursor crosshair center when aligned.

E. DERIVATION OF CORRECTION TERMS INCLUDING OFFSET

In Figure 25 the geometric relationships of the linear array with respect to the function being traced are shown. For clarity, dimensional distances of the three sample points shown have been exaggerated. Consequently, significant differences in slopes between the points indicate angular positional error of the array in perpendicularity to the function. In the practical case, where sample dimensions are closely spaced, these errors are greatly reduced to second-order magnitudes in their effects on computed correctional terms.

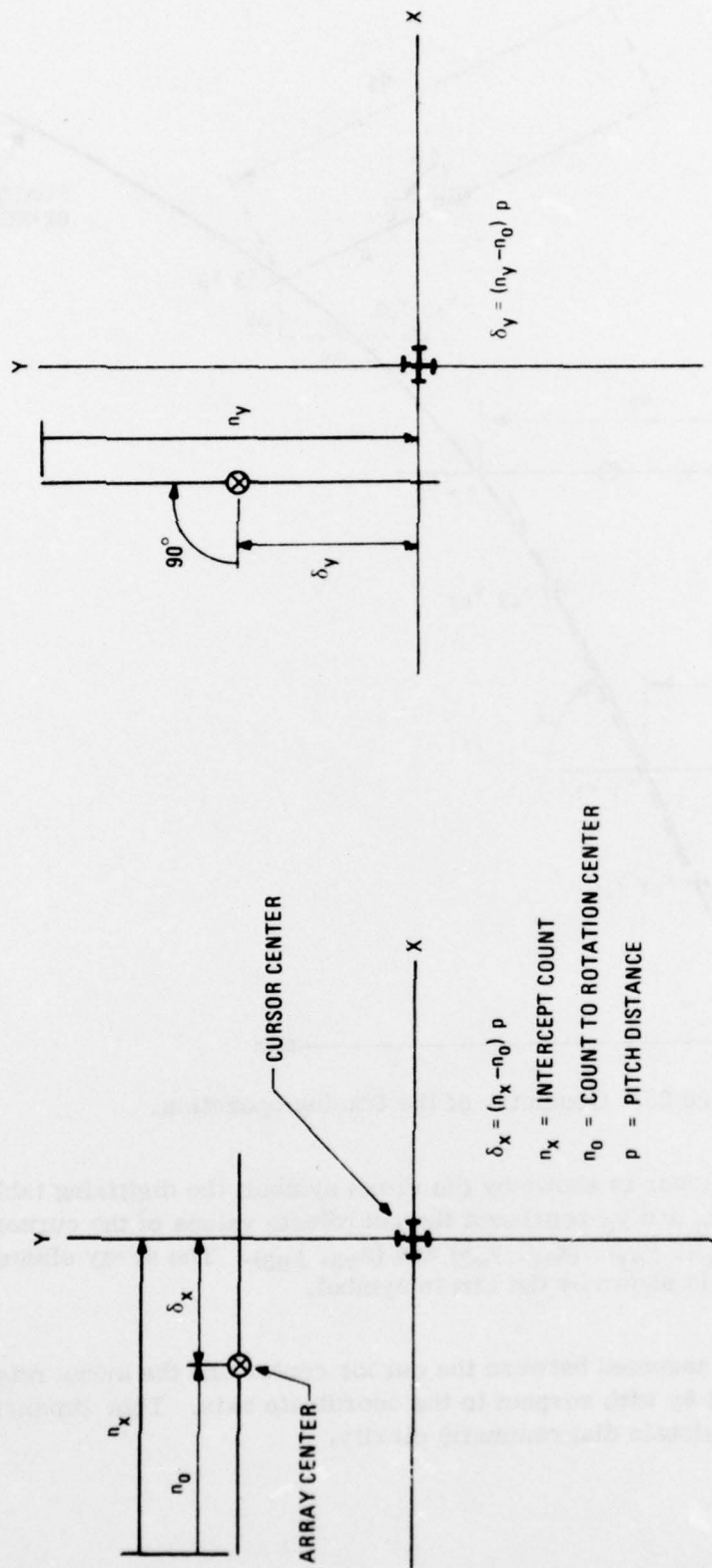


Figure 24. Determining array and crosshair offset values by output count differences to a reference coordinate axis.

The distance from the reference array element at which the scan starts to the rotational axis is shown as d_0 ; the distance to the detected element is shown as d_1 , d_2 , and d_3 . These distances are given by

$$d_i = p n_i$$

p = array element pitch distance

n_i = number of array sample pulses counted from the array reference element at which the function is detected at sample point i .

The first two cursor samples, designated (x_{e1}, y_{e1}) and (x_{e2}, y_{e2}) , are shown as accurately tracking the function to allow computation of the initial array orientation. The third cursor position, represented by (x_{e3}, y_{e3}) , shows how correction terms are derived as the cursor deviates in position from the traced function.

From the geometry it can be seen that the value of the array intercept with the traced function with respect to the encoder value is given by

$$x_i = x_{ei} + \Delta x_i$$

$$y_i = y_{ei} + \Delta y_i$$

$$\text{where } \Delta x_i = (d_i - d_0) \cos \theta - \delta x$$

$$\text{and } \Delta y_i = \delta y - (d_i - d_0) \sin \theta.$$

The array rotational angle for orthogonality to the traced curve, θ , is based on the initial slope of α computed from previous coordinate pairs and is calculated as

$$\theta = \left(\alpha - \frac{\pi}{2} \right)$$

The initial value of α is obtained by an accurate trace of the curve for at least the first pair of coordinate samples, and can be computed directly from the encoder values as

$$\alpha = \arctan \frac{y_{e2} - y_{e1}}{x_{e2} - x_{e1}}$$

At x_{e3} and y_{e3} in Figure 25 the array is shown rotated through this angle.

F. GRADICON SYNCHRONIZED VERSUS NONSYNCHRONIZED ARRAY OUTPUT

Initially it was proposed in our design to allow the array scan clock to free-run, independent of instants at which Gradicon output values occurred. If the scan rate could be made sufficiently high, the array output could be obtained within a corresponding one-resolution interval for a given maximum tracking rate.

Another mode of operation was also considered and implemented within the processing hardware. This mode activated the array scan clock at the instants at which Gradicon output values occurred, thus time synchronizing the array output to the Gradicon. This mode was investigated to determine if any signal gain could be achieved operating in this manner by a resultant increased integration time, and to provide flexibility in the computer data transfer logic by sequencing the input operating directly from the Gradicon pulse.

Figure 26 shows the output time sequence for the cases of nonsynchronized and synchronized modes, (a) and (b), respectively. In the case of nonsynchronized operation, laboratory testing showed that adequate signal integration could be achieved at a 25-kHz scan clock rate.* At the end of each scan interval, eight clock periods are provided for resetting the outputs to zero so that each successive scan produces a detected output. This clock rate sets the maximum tracking rate at 0.7 in/s to output the correction factor within one array resolution element of motion. As shown, the array output will be produced within 3 ms of a Gradicon output value.

With no change in this clock rate, operating in a Gradicon-synchronized mode allows the array to saturate even in the 14-ms period between Gradicon pulses at the maximum scan rate. Thus, two scan periods are required to produce a valid array output detection sample. The first scan serves only to reset the array to zero, with the second scan resulting in a detectable output approximately 5.1 ms after the Gradicon output. This delay would exceed the allowable time for obtaining data within a one resolution motion of the array. It becomes obvious that the array clock rate and the tracing velocity must be related to produce a constant integration time to maintain a consistent (invariant) signal level for a given feature. While it appears possible to increase the tracing rate by using a controlled variable frequency array sampling clock, it was regarded as an added technical complexity not required for demonstrating feasibility of the aided-track concept.

*This rate was established on an experimental light table with a background source intensity in the rough order of the Gradicon table. This clock rate is therefore subject to change for operation on the Gradicon table. Initial testing showed that this clock rate may be increased somewhat.

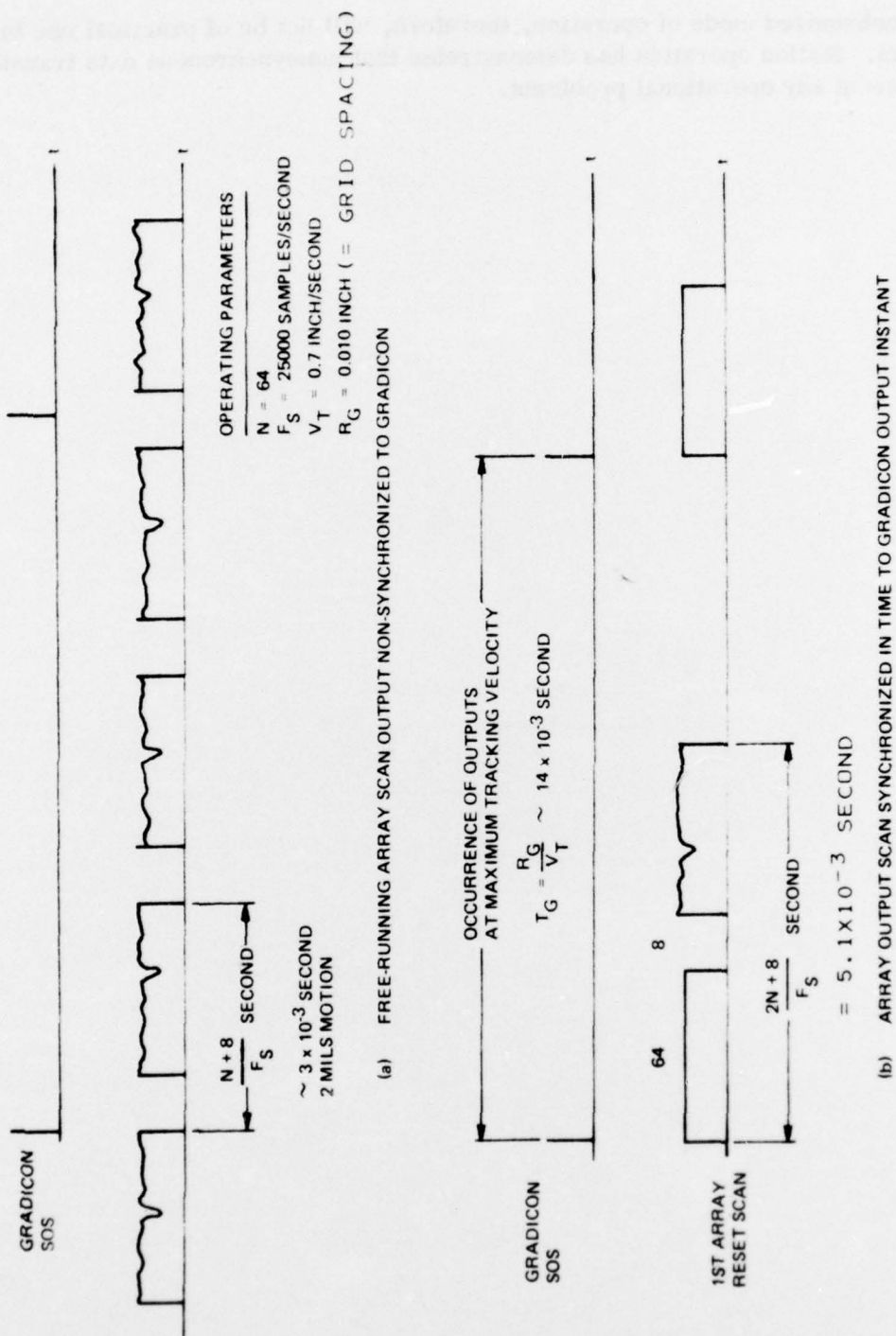


Figure 26. Comparison of output timing for array scans synchronized and asynchronous with Gradicon conversions.

The synchronized mode of operation, therefore, will not be of practical use in this program. Station operation has demonstrated that nonsynchronous data transfer does not present any operational problems.

